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U. S. A R M Y

TRANSPORTATION RESEARCH COMMAND  
FORT EUSTIS, VIRGINIA

TRECOM TECHNICAL REPORT 63-35

CATALOGED BY DDC

AS AD No.

THE TURBULENT BOUNDARY LAYER IN ZERO-PRESSURE  
GRADIENT WITH TRANSPIRATIONTask 1D121401A14203  
(Formerly Task 9R38-11-009-03)  
Contract DA 44-177-AMC-892 (T)

July 1963

64-6

prepared by:

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418754

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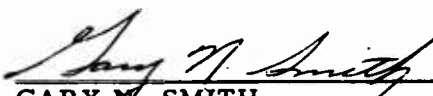
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HEADQUARTERS  
U S ARMY TRANSPORTATION RESEARCH COMMAND  
FORT EUSTIS, VIRGINIA

A review of this report was conducted for the Government by the U. S. Army Transportation Research Command. Emphasis of this report is on the comparison of several methods for determining the surface shear of boundary layers with and without transpiration. An interesting feature of this investigation is the boundary layer tunnel that was especially designed and built for studying turbulent boundary layers with or without transpiration.

On interpretation of the data generated by this study, no superior accuracy of one method over another could be shown, and comparisons in general appeared to be inconclusive.

  
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Task 1D121401A14203  
(Formerly Task 9R38-11-009-03)  
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THE TURBULENT BOUNDARY LAYER IN ZERO-PRESSURE  
GRADIENT WITH TRANSPIRATION

Aerophysics Research Report No. 40

Prepared by  
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for  
U. S. ARMY TRANSPORTATION RESEARCH COMMAND  
FORT EUSTIS, VIRGINIA

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## SYMBOLS

A	Wall law constant (taken here as 5.60)
B	Wall law constant (taken here as 5.60)
$C_f$	Skin friction coefficient,
H	Boundary layer shape parameter,
ln	Logarithm to base e
$R_\theta$	Reynolds number based on momentum thickness,
U	Local free-stream velocity, feet per second
U'	Local free-stream velocity gradient in x-direction, feet per second per foot
$U_\tau$	Friction velocity, $\sqrt{\tau_0/\rho}$ , feet per second
u	Velocity within the boundary layer in x-direction, feet per second
$v_0$	Velocity at surface in y-direction, feet per second
x	Distance measured parallel to surface, feet
y	Distance measured perpendicular to surface, feet
$\chi$	Wall function, Table 1
$\beta$	Wake function, Table 1
$\gamma$	Transpiration function, Table 1
$\delta$	Distance in y-direction to edge of boundary layer, feet
$\delta^*$	Displacement thickness, $\int_0^\infty (1 - \frac{u}{U}) dy$ , feet
$\nu$	Kinematic viscosity, square feet per second
$\rho$	Fluid density, slugs per cubic foot
$\tau_0$	Surface shearing stress, pounds per square foot
$\theta$	Momentum loss thickness, $\int_0^\infty \frac{u}{U} (1 - \frac{u}{U}) dy$ , feet

Subscripts

- |   |   |
|---|---|
| o | Denotes conditions at surface ( $y = 0$ ) |
| w | Denotes component due to wake law         |

Superscript

- |   |                                 |
|---|---------------------------------|
| . | Denotes gradient in x-direction |
|---|---------------------------------|

## INTRODUCTION

The need for an accurate method of evaluating drag has become increasingly acute with the development of today's high-performance aircraft. Of particular interest is skin friction, the effects of which govern, to a large extent, the lifting capabilities as well as the maximum speed of aircraft.

Until recently, little practical application has been made of boundary layer control by fluid injection and suction through the surface, but past research and recent experiments (References 1, 2, and 3) have shown the practicality of these techniques in obtaining low drag and high lift. Accurate methods for determining the surface shear in such cases are often required for proper evaluation of the various systems. The development of methods for measuring skin friction depends in many cases upon experimental data from which the shear values are calculated, and these methods often show considerable variation.

This report is concerned with the comparison of several methods for determining the surface shear of boundary layers with and without transpiration through the surface. Flat-plate conditions, taken here as denoting zero pressure gradient, were maintained throughout the tests.

## EXPERIMENTAL APPARATUS AND TECHNIQUES

### Apparatus

The tunnel used in these tests was constructed especially for studying turbulent boundary layers with or without transpiration (Figure 1). Measurements of the boundary layer were taken on a vertical test section which was opposite a flexible metal wall used to maintain the desired pressure gradients along the test section. A system of cranks, which pivoted on the tunnel floor and ceiling and were bonded to the flexible wall, allowed the wall to be moved, thereby adjusting the free-stream velocity and velocity gradient.

The removable test section consisted of an open-sided plywood box to which a sheet of 0.027-inch aluminum was fastened as shown in Figure 2. Knife-edged aluminum supports inside the box supported the sheet and prevented deflections when suction was applied. Stiffeners bonded to the inside of the metal sheet resisted outward deflections due to high pressures inside the box when air was injected into the boundary layer. The injection and suction compartments of the box were separated by a rubber seal held in place against an aluminum brace by the pressure differential between the two compartments.

Ten flush static taps were bonded to the inside of the aluminum plate, from which plastic tubing was led to a ten-position manual scanner valve. Small holes were drilled along the plate to allow a total head probe to extend through the wall in line with the static orifices (Figure 3). A pressure tap was located in each end of the box for the purpose of obtaining the pressure difference across the test wall. A pump was attached to the box to suck air from the boundary layer through the perforated plate of the test section. All joints of the test section and tunnel walls were sealed to prevent leakage of air into the tunnel.

Power for the tunnel was supplied by a 2.25-horsepower, 28-volt, motor driving a Joy Axivane fan. A Sola constant voltage transformer damped the line voltage fluctuations, and a powerstat connected to a rectifier was used to vary the tunnel speed.

Air for transpiration was supplied by a 2-horsepower Cadillac centrifugal pump.

### Instrumentation

The probe used in taking velocity profiles was made of progressively smaller diameter stainless steel tubing ending in a piece of flattened,

thin-wall copper tubing. A micrometer adjustment on the probe allowed the measurement of distances from the wall to the nearest 0.001 inch (Figure 4). To insure that the probe was touching the wall for the initial measurement, an electrical circuit containing a battery and light was connected between the metal wall and the probe. Contact of the probe tip with the wall completed the circuit and thus caused the bulb to glow.

Velocity profiles were measured with a Kollsman helicopter air-speed indicator calibrated against a Betz manometer, while very small differential pressures across the test wall were measured with a Magnehelic pressure indicator sensitive to 0.01 inch of water. The velocity gradient in the direction of the flow was established by using a ten-position scanner valve connected to an airspeed indicator to quickly measure the free-stream velocity of each of the ten stations along the test section.

Injection and suction velocities were measured with a calibrated venturi to indicate flow rates, and an airspeed indicator was used to measure the pressure drop across the test wall.

#### Experimental Methods

The desired zero-velocity gradient was set by adjusting the tunnel speed until the velocity at the first position was 88 feet per second. Then, with the total head probe in the free-stream, the other nine static orifices were individually sampled by means of the scanner valve. The wall was adjusted until a zero-velocity gradient had been obtained at all ten stations. In the case of suction or injection through the surface, the desired suction or injection velocity was set prior to adjusting the pressure gradient since, with the addition or removal of fluid, the velocity gradient was found to change slightly. Thus, with each new transpiration velocity, the wall was readjusted to maintain a constant free-stream velocity of 88 feet per second. During the tests, it was found that a pump was required to produce the desired suction velocities; however, the required injection velocities could be obtained by allowing the ambient air to flow into the box as a result of the lower pressure in the tunnel. Restriction of the intake tube regulated the injection velocities as desired.

The perforated metal plate was calibrated by measuring the total quantity flow through the plate for a given pressure drop across the skin. Injection or suction velocities were found by dividing the total quantity flow by the area of the plate, thus allowing a calibration curve to be drawn of transpiration velocities versus pressure drop across the skin.

Velocity profiles in the boundary layer were measured first at the most downstream position (position 10) and then at each of the other upstream positions. After the velocity gradient and transpiration conditions

had been established and the boundary layer probe had been installed at a given station, the probe was moved until contact with the wall was indicated by the glowing light. The first measurement recorded was at a height of 0.005 inch; the distances from the surface to the upper inside wall of the probe and from 25 to 52 points were obtained for a velocity profile.

## DISCUSSION OF RESULTS

A number of profiles were measured on the impervious wall and also for the cases of transpiration with injection and suction through the wall. Different methods of analysis which were applied to the experimental profiles allowed a comparison of the measured skin friction values with those predicted by existing theories.

### Methods for Determination of Skin Friction

Several methods for the determination of shear were investigated, among them being the boundary layer momentum equation as derived by integration of Prandtl's two-dimensional incompressible boundary layer equations. These equations, when integrated, give

$$\theta' = \left( \frac{U_\tau}{U} \right)^2 - \frac{\theta U'}{U} (H+2) + \frac{V_0}{U} \quad (1)$$

For the case of the impervious wall with zero-pressure gradient,  $U' = 0$  and  $V_0 = 0$ , which causes (1) to take the form

$$C_f = 2 \theta' \quad (2)$$

where the prime denotes the derivative with respect to  $x$ . From a plot of  $\theta$  versus  $x$ , the value of  $\theta'$  can be measured and the local skin friction calculated. The effects of transpiration at the surface may be included if the suction or injection velocity,  $V_0$ , is known. When this value is placed in the equation for the case of the flat plate with transpiration, the momentum equation becomes

$$C_f = 2 \left( \theta' - \frac{V_0}{U} \right) \quad (3)$$

where  $V_0$  is negative for suction and positive for injection. Thus the integrated property,  $\theta$ , of the boundary layer profile can be used to determine the local skin friction.

For the impervious flat-plate conditions, there are a number of skin-friction relations such as those by Prandtl-Schlichting, Coles,

Cornish, and Rubesin as shown in Figure 5. These skin-friction relations, which generally result from the assumption of some power law or log law for the boundary layer profile, usually show the skin friction coefficient plotted as a function of the boundary layer momentum thickness Reynolds number.

With the establishment of the existence of the wall law in turbulent boundary layer theory (Reference 4), many new techniques for the determination of skin friction have been brought forth. One of the best known is that due to Clauser (Reference 5). The wall law

$$\frac{U}{U_\tau} = A + B \log \frac{y U_\tau}{\nu} \quad (4)$$

is shown in Figure 6 with a profile which has been fitted to this law using Clauser's method and assuming  $A = B = 5.6$ . Clauser's method involves fitting the linear portion of the experimental profile in question to a family of curves with  $\frac{U}{U_\tau}$  as the ordinate and  $\log \frac{y U_\tau}{\nu}$  as the abscissa (Figure 7). Most impervious turbulent boundary layer profiles can be fitted to these universal curves, and in this manner the skin friction may be determined.

A method due to Cornish (Reference 6) utilizes a description of the entire profile rather than only the wall law region. This description of the profile is given by the equation

$$\frac{u}{U} = 1 + \frac{U_\tau}{U} \left( \alpha + \beta \frac{U_w}{U_\tau} \right) \quad (5)$$

which was derived from the law of the wall and Cole's wake law. Data from experimental profiles can be analyzed not only in the wall law region but also throughout the entire profile thickness.

This profile description can be extended to the case of transpiration with injection or suction through the surface, and the resulting equation becomes

$$\frac{u}{U} = 1 + \left( \frac{U_\tau^2 + V_0 U}{U^2} \right)^{\frac{1}{2}} \alpha + \frac{U_w}{U} \beta + \frac{V_0}{U} \gamma. \quad (6)$$

In this equation, as well as in the impervious case,  $\alpha$ ,  $\beta$ , and  $\delta$  are predetermined constants which are functions only of  $y/s$  (see table). From a given profile, with known suction or injection velocity, the unknown parameters  $U_r$  and  $U_w$  may be found by simultaneously solving any pair of points on the profile.

Computer methods, using all of the data points in a profile to determine the root mean square values of  $U_r$  and  $U_w$ , allow the profiles to be more closely analyzed, thus yielding a more accurate value of the skin friction. Combinations of three measured points gave three pairs of points which, when treated in the above fashion, yielded consistent values of  $U_r$  and  $U_w$ . Good agreement was obtained when all of the data points were then plotted on the profile resulting from equation 6 (see Figure 8).

Another method for obtaining shear for profiles with transpiration through the surface is that due to Black and Sarnecki (Reference 7). This method is based on a bilogarithmic law of the wall for turbulent boundary layers which is written as

$$U_r^2 + U_0 U = \left( \frac{U_0}{2k} \ln \frac{y}{s} \right). \quad (7)$$

This law holds for all nearly two-dimensional flows where  $\frac{dP}{dy} = 0$  and where the laminar sublayer does not occupy a large portion of the boundary layer thickness. In this method, with injection at the surface, the profile in question is plotted as in Figure 9. A nondimensional parameter is defined by the equation

$$y_i = \frac{1}{2k} \sqrt{\frac{U_0}{U}} \ln \frac{yU}{s} \quad (8)$$

where  $k$  is a mixture length constant, here taken as 0.182, and  $U_0$  is the injection velocity. The parameter  $\frac{U_0}{U} = y_i^2$  is plotted as the ordinate of a graph with  $y_i$  as the abscissa. When thus displayed, the profile exhibits a bilogarithmic region through which a straight line can be drawn (Figure 9). The value of the skin friction coefficient may then be determined by the following function of the slope of the line and its intercept on the ordinate:

$$C_f = 2 \frac{U_0}{U} \left[ m + \left( \frac{m}{2} \right)^2 + y_i @ y_i = 1.0 \right] \quad (9)$$

where  $m$  is the slope and  $y$  is the  $\frac{u}{U} - y_i'$  value at  $y_i' = 1.0$ . Black and Sarnecki apply the same method to the case of suction but make slight changes in the method used to plot the injection profiles (Figure 10). In this case the abscissa is taken as

$$y_s = \frac{1}{2K} \sqrt{\frac{-V_0}{U}} \ln \frac{yU}{V} \quad (10)$$

where the suction velocity,  $V_0$ , is negative and the ordinate is plotted as  $\frac{u}{U} + y_s^2$ . With suction, then the skin friction coefficient becomes

$$c_f = 2 \frac{V_0}{U} \left[ -m + \left( \frac{m}{2} \right)^2 + y @ y_s = 1.0 \right] \quad (11)$$

where  $y$  is the  $\frac{u}{U} + y_s^2$  value at  $y_s = 1.0$ . Examination of Figures 7 and 8 shows that the length of the bilogarithmic law region increases as the boundary layer thickness increases. For the case of highly sucked boundary layers, the bilogarithmic region becomes small, thus causing errors in the measurement of the slope and the intercept of the experimental data.

The dotted lines on Figures 9 and 10 are the parabolas representing the extreme limits  $\frac{u}{U} = 0$  and  $\frac{u}{U} = 1.0$  which will bound any experimental data. The intercept point of the bilogarithmic line with the bounding parabola corresponding to  $\frac{u}{U} = 1.0$  is determined by the shear of the experimental profile. For the case of suction, this intercept point also indicates whether the boundary layer momentum thickness is increasing, is decreasing, or has a constant value in the downstream direction.

With fluid injection, Black and Sarnecki have pointed out that an experimental profile may have negative effective shear due to conditions in the laminar sublayer. The shear at the wall is described by the expression

$$\tau_0 = \mu \frac{\partial u}{\partial y} - \rho \overline{u'v'} \quad (12)$$

If the Reynolds stress term  $\rho \overline{u'v'}$  is greater in magnitude than the viscous term  $\mu \frac{\partial u}{\partial y}$ , the equation for  $\tau_0$  will yield a negative effective shear. As in the case of suction, the intercept of the line through the bilogarithmic region with the bounding parabola is determined by the shear conditions and will predict whether the shear is positive, zero, or negative.

### Analysis of Experimental Data

The experimental flat-plate profiles measured in these tests are presented in Figure 11 in nondimensional form, and a graph of  $\theta$  versus  $x$  is shown in Figure 12. The previously discussed methods of skin friction determination for impervious surfaces were applied to the experimental data and compared with a number of theories. Figure 13 shows a comparison of the flat-plate relations with three methods used to reduce the experimental data. As can be seen, the Cornish profile method and the Clauser profile method exhibit about a 30 percent variation. Of the two, the Clauser method seems to compare more favorably with the flat-plate relations, but the momentum equation yielded such widely scattered data that it was of little use in the analysis. Three-dimensional flows and difficulty in obtaining accurate values of the slope,  $\theta$ , have an adverse effect on the use of the momentum equation to determine surface shear at a point.

The boundary layer profiles measured with suction at the surface are shown in Figure 14. In this case, the suction velocity was nearly constant along the test section, as was the free-stream velocity. These conditions, if maintained over a great enough distance, would eventually cause the boundary layer to become asymptotic, that is, cause  $\frac{d\theta}{dx} = 0$ . An examination of Figure 15 shows that when suction is applied at  $x = .75$  foot,  $\theta$  increases less rapidly and then decreases to a constant value at the last two stations, indicating that the asymptotic state has been reached. Figure 16 is a nondimensional plot of the two asymptotic profiles and shows that they may be superimposed on the same curve. They also compare favorably with the predicted result of the Cornish profile method. A graph of  $C_f$  versus  $Re$  for the suction case shows variations which are exaggerated by the very large horizontal and vertical scales (Figure 17). The momentum equation seems to be in good agreement in most cases with the Black and Sarnecki method, while in all cases the Cornish method predicts higher skin-friction values.

In the course of measuring the injection profiles, an unusual condition was noticed in which the velocity profiles showed a local inflection near the surface (Figure 18). The position of the probe with respect to the rows of holes made no apparent difference in the measured profile shape. The absence of this local inflection in the impervious or suction cases indicated that the condition was due solely to the manner in which air was injected into the boundary layer. The effect of protuberances on the test wall was investigated by the addition of a strip of tape placed normal to the flow. This strip did not alter the inflected region in any way. It was further established that no ambient air was escaping into the test section.

A series of profiles measured at position two with varying injection rates is shown in Figure 18. It may be observed that at the lower injection

rates the profile does not exhibit as severe an inflection as it does when the injection rate is increased.

Effects of the porosity on the injection profiles had not previously been considered in this experiment, since it was felt that a row spacing at 1/4 inch with 10 holes per inch approximated completely porous conditions. However, the obvious dependence of the profile inflection upon the rate of injected flow indicated that localized or discrete disturbances were being caused by the jets of injected flow through the perforations. Therefore, the porosity was increased and the velocity through the holes was decreased by enlarging the holes in the injected region from 0.018 inch to 0.033 inch. In this manner, the same value of quantity flow could be passed through the surface, that is,  $\frac{Q}{A}$  held constant, but the jet velocity of the injected flow was reduced. Additional measurements at position two did not exhibit the local inflection and agreed reasonably well with the profile predicted by equation 6 (see Figure 18).

A third set of profiles was measured along the test section and is shown in Figure 19. The momentum thickness showed rapid growth in the injection region, less growth in the suction region, and  $\delta$  decreasing near the end of the test section, indicating a slightly oversucked boundary layer (Figure 20).

Calculations and comparison of the skin friction for the injection profiles yielded negative values of shear for five of the six points shown on Figure 21, and there was considerable scatter among the points. Close agreement was attained between the Cornish profile and Black and Sarnecki profile methods.

The results of the suction case show considerable scatter (Figure 21). With only one exception, the Cornish profile method predicted the highest shear and the Black and Sarnecki method was about 50 percent lower. In two instances, the momentum equation predicted negative shear, which would appear to be in error since both points were in the suction region.

In summation, the agreement among the various methods in all of the cases was poor, despite the fact that rather accurate measurements were made of the boundary layer profiles. The determination of shear in the cases of transpiration through the surface was also dependent upon a knowledge of local transpiration quantities, and variation in  $\frac{Q}{A}$  were reflected in the shear data.

### CONCLUDING REMARKS

The determination of surface shear is highly dependent upon the establishment of nontransient flow conditions and upon accurate measuring techniques. The flows studied should be two-dimensional to comply with the basic assumption of most theories. Wind-tunnel tests to evaluate the effectiveness of several methods for determining shear on surfaces with and without transpiration showed the following results.

For the impervious case, the Clauser method yielded shear values 15 percent higher than the Cornish method, with a maximum variation of 30 percent. In both cases, the shear values fell below that for the flat-plate relations included in this comparison. The Cornish profile relation does have the advantage of being able to predict the entire profile shape, which in all cases compared well with the experimental data. The momentum equation yielded values of shear too scattered to be of value in the comparison.

The method of Black and Sarnecki, the method of Cornish, and the momentum equation showed considerable disagreement for the suction case. Of the methods considered, the momentum equation was found to be about 25 percent higher than the shear found by the Black and Sarnecki profile method. Shear found by the Cornish profile method was in most cases from 75 percent to 100 percent higher than that predicted by the Black and Sarnecki method.

Determination of shear with fluid injection through the surface appears to be a fluid in which there is a need for improvement. Use of the Cornish or Black and Sarnecki profile method predicted negative shears, as did the momentum equation. Comparison of one method with another was unproductive due to the large amount of scatter.

With injection of fluid into the boundary layer through perforations in the surface, the assumption of continuous transpiration is difficult to realize, since the flow emerges through each hole as a jet and distorts the boundary layer profile. Suction through perforations apparently produces less discrete effects.

From this study, it is obvious that the determination of surface shear from the boundary layer profile is, at best, uncertain. None of the methods examined could be shown to be superior or more accurate than the others; however, the momentum equation appears to be less consistent than the other methods.

The need for a method of experimentally determining the surface shear for the case of transpiration without reference to the boundary layer

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TABLE  
PARAMETERS FOR UNIVERSAL PROFILE DESCRIPTION

$y/\delta$	$\alpha$	$\beta$	$\gamma$
0.00	--	-1.00	---
0.01	-11.20	-1.00	31.36
0.02	- 9.52	-1.00	22.50
0.05	- 7.28	-0.99	13.30
0.10	- 5.60	-0.97	7.84
0.20	- 3.86	-0.90	3.78
0.30	- 2.74	-0.79	2.15
0.40	- 1.99	-0.65	1.24
0.50	- 1.39	-0.50	0.71
0.60	- 0.94	-0.35	0.38
0.70	- 0.58	-0.21	0.19
0.80	- 0.36	-0.10	0.07
0.90	- 0.16	-0.02	0.02
1.00	0.00	0.00	0.00

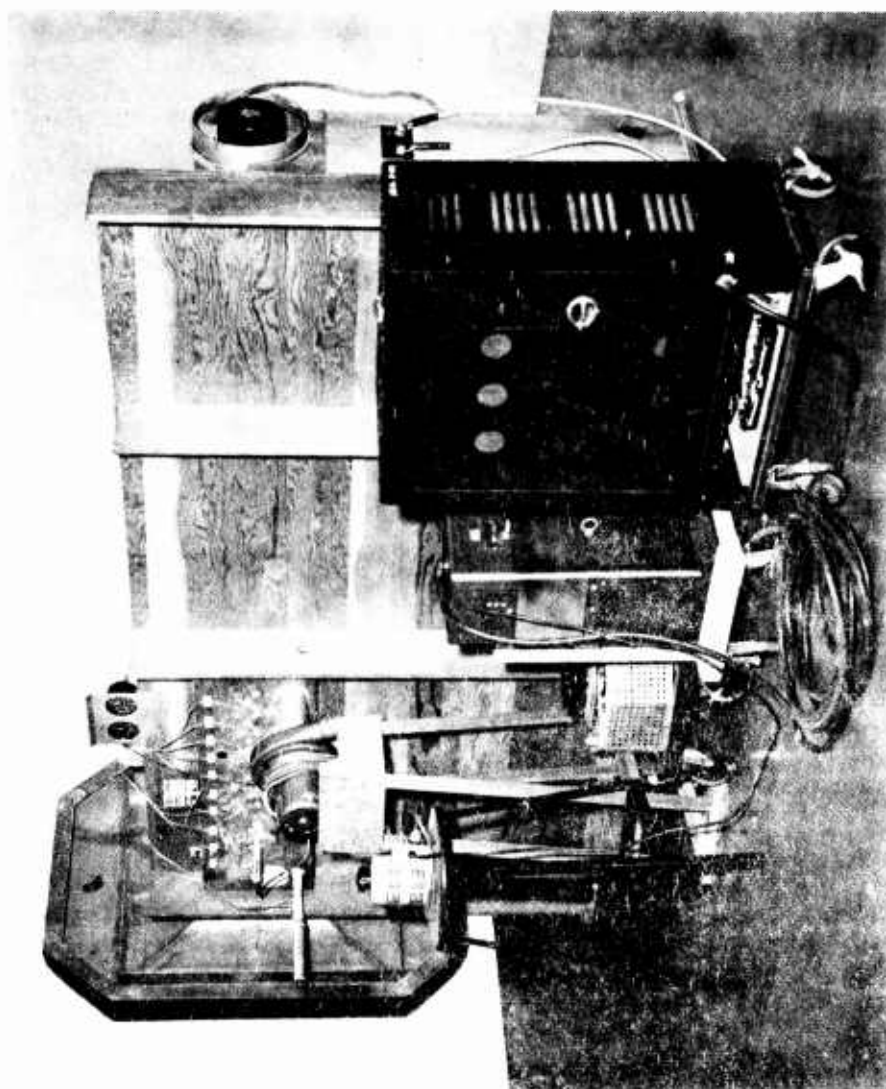
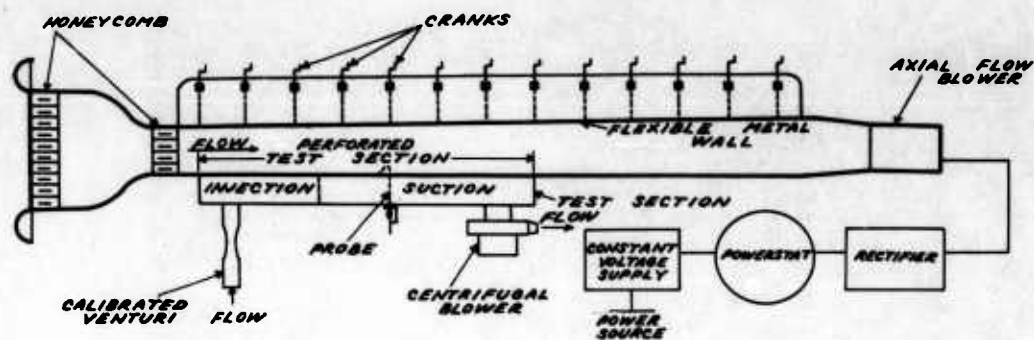
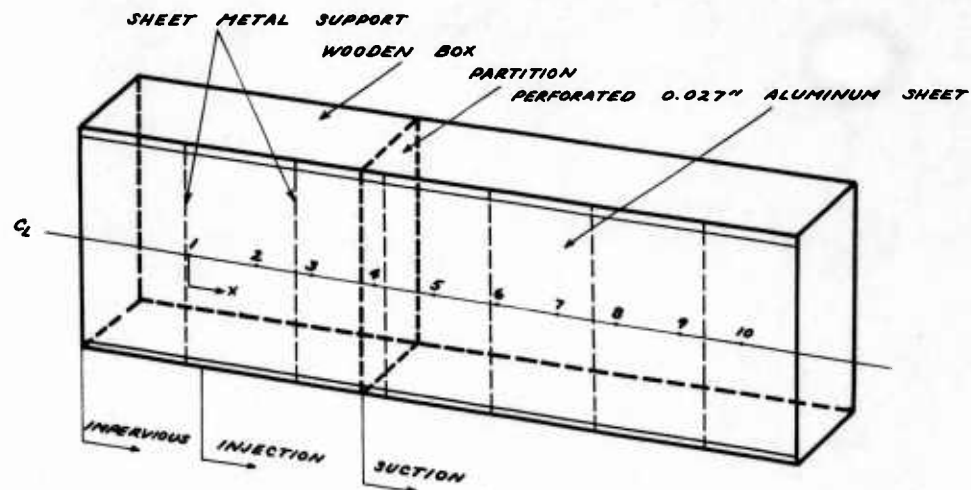


Figure 1. Boundary Layer Research Tunnel.



### TEST SECTION



PROBE POSITION	1	2	3	4	5	6	7	8	9	10
DISTANCE X FT	0	0.2491	0.496	0.758	1.001	1.26	1.49	1.75	1.99	2.24

Figure 2. Schematic Diagram of Boundary Layer Research Tunnel and Test Section.

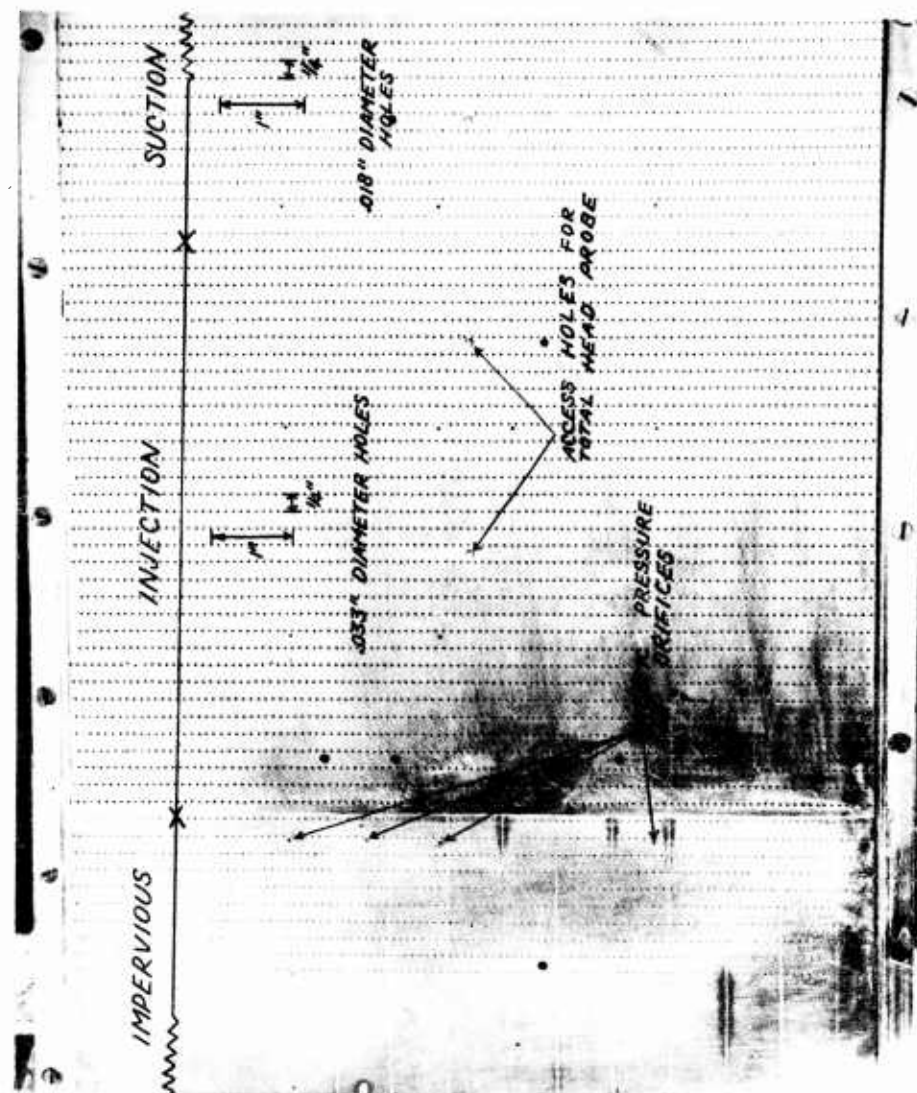
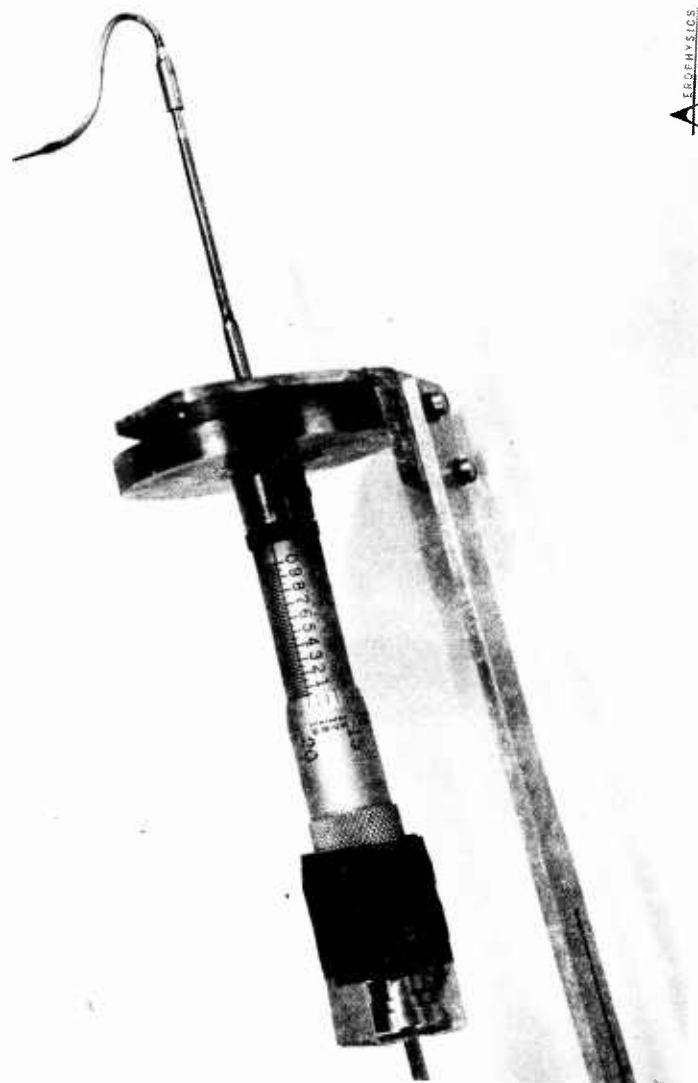


Figure 3. Perforated Surface.



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Figure 4. Boundary Layer Probe.

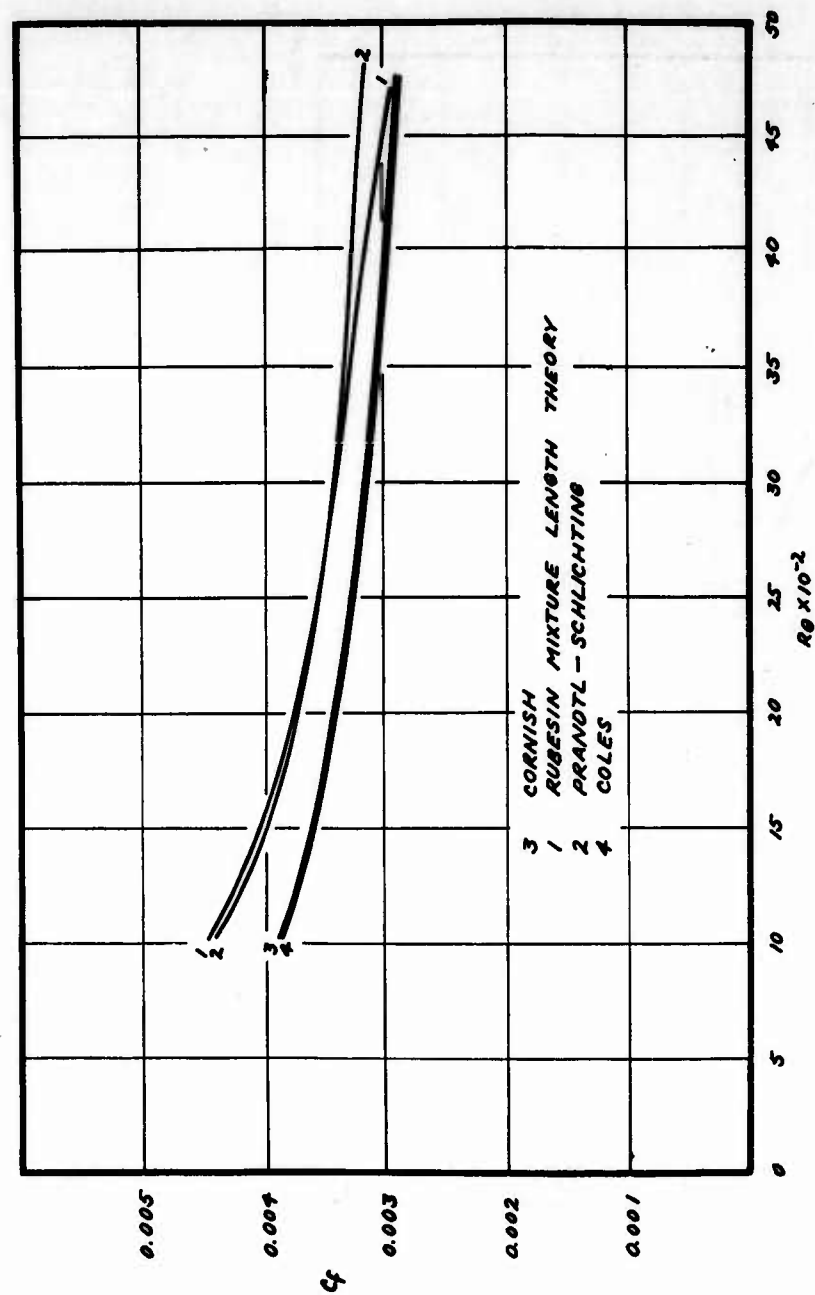


Figure 5. A Comparison of Flat-Plate Skin-Friction Relations.

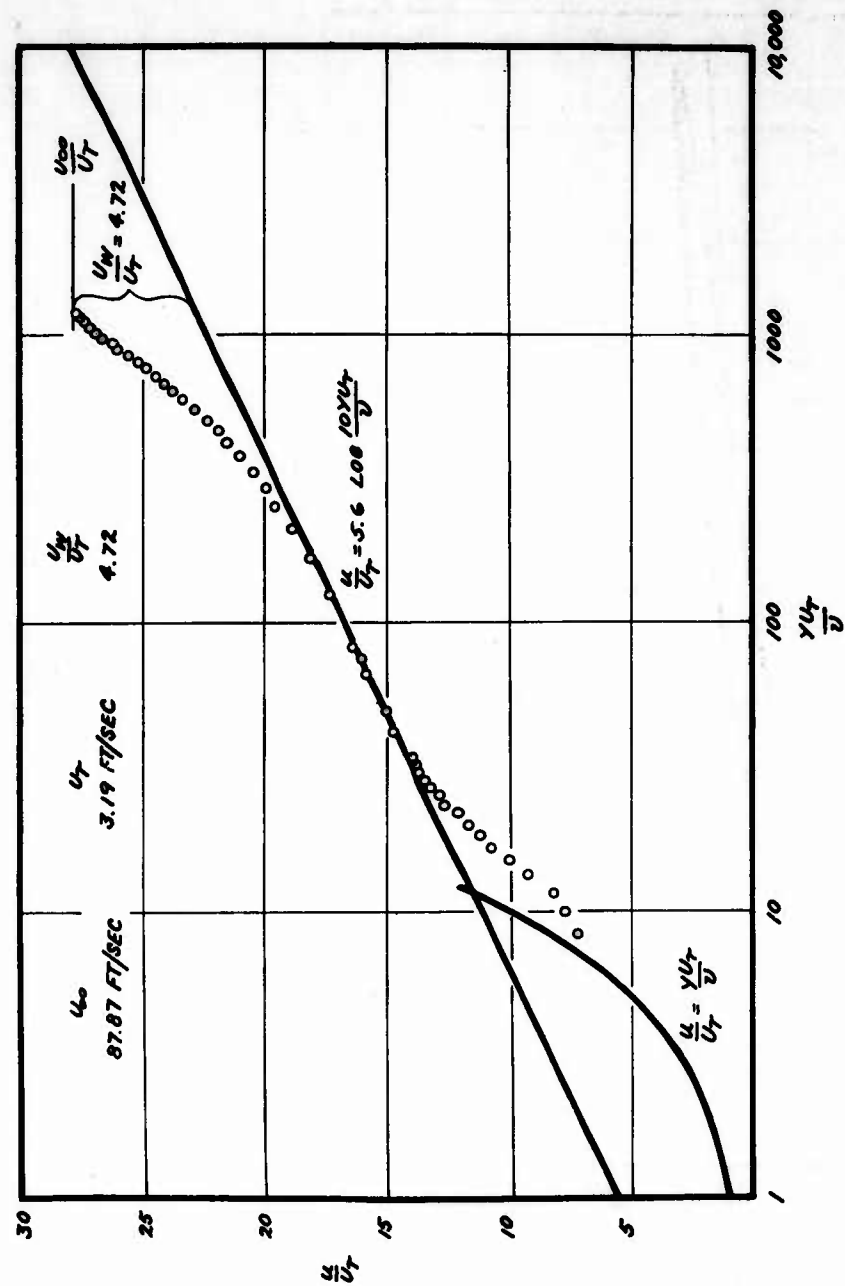


Figure 6. Law of the Wall for Turbulent Boundary Layers.

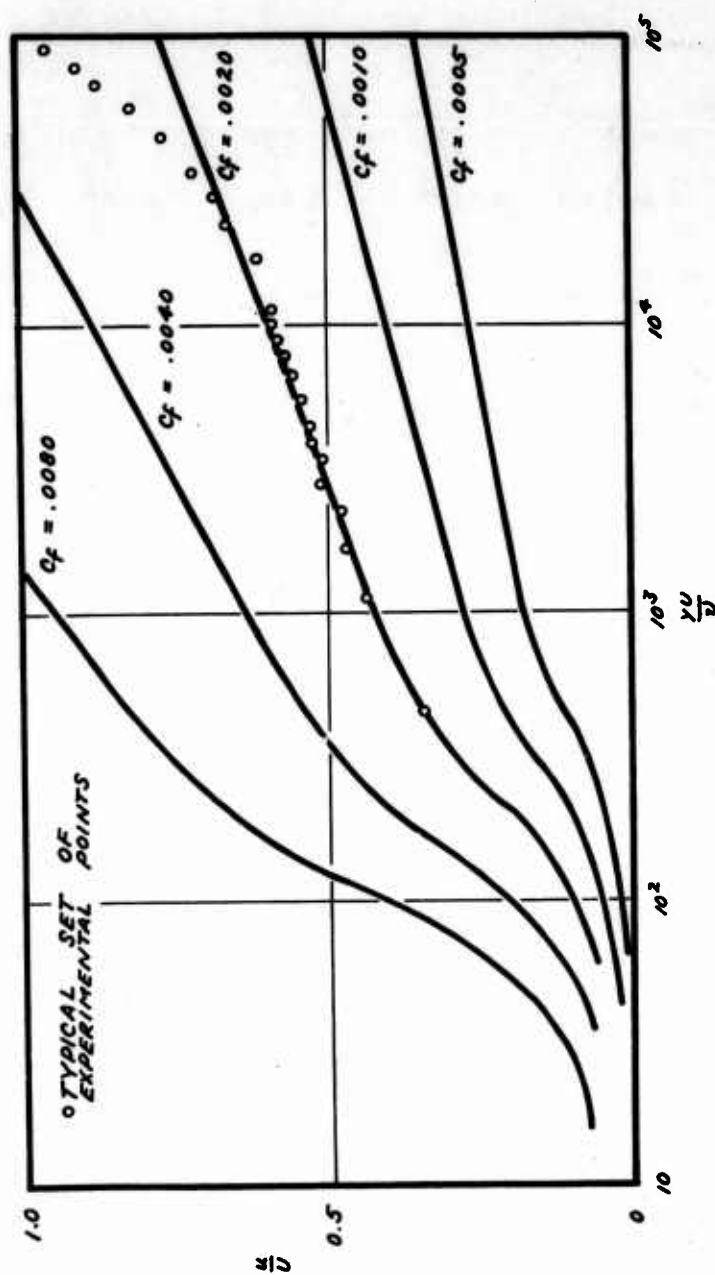


Figure 7. Clauser's Chart for Determination of Turbulent Skin Friction.

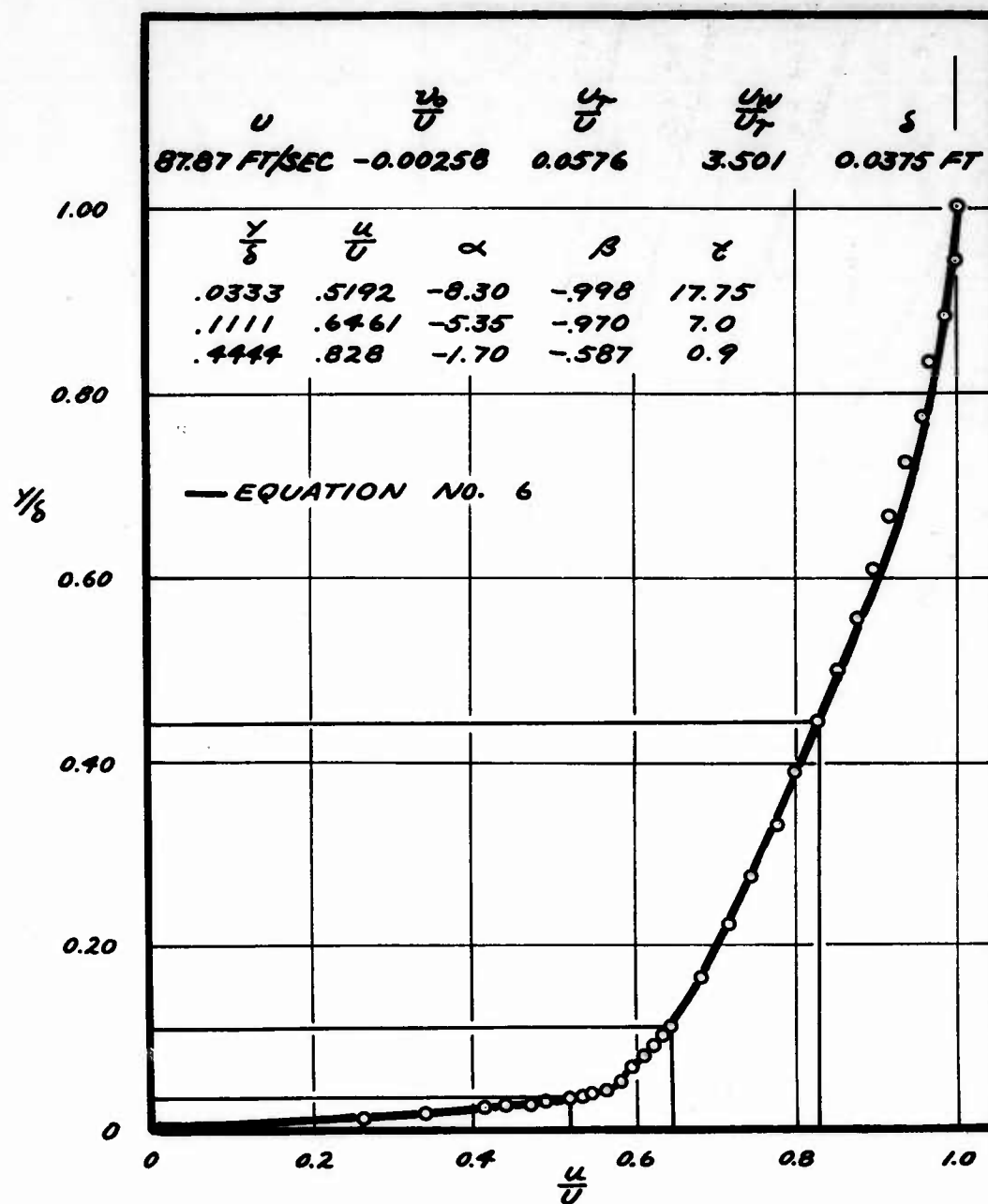


Figure 8. Typical Boundary Layer Suction Profile with Analysis by Cornish's Method.

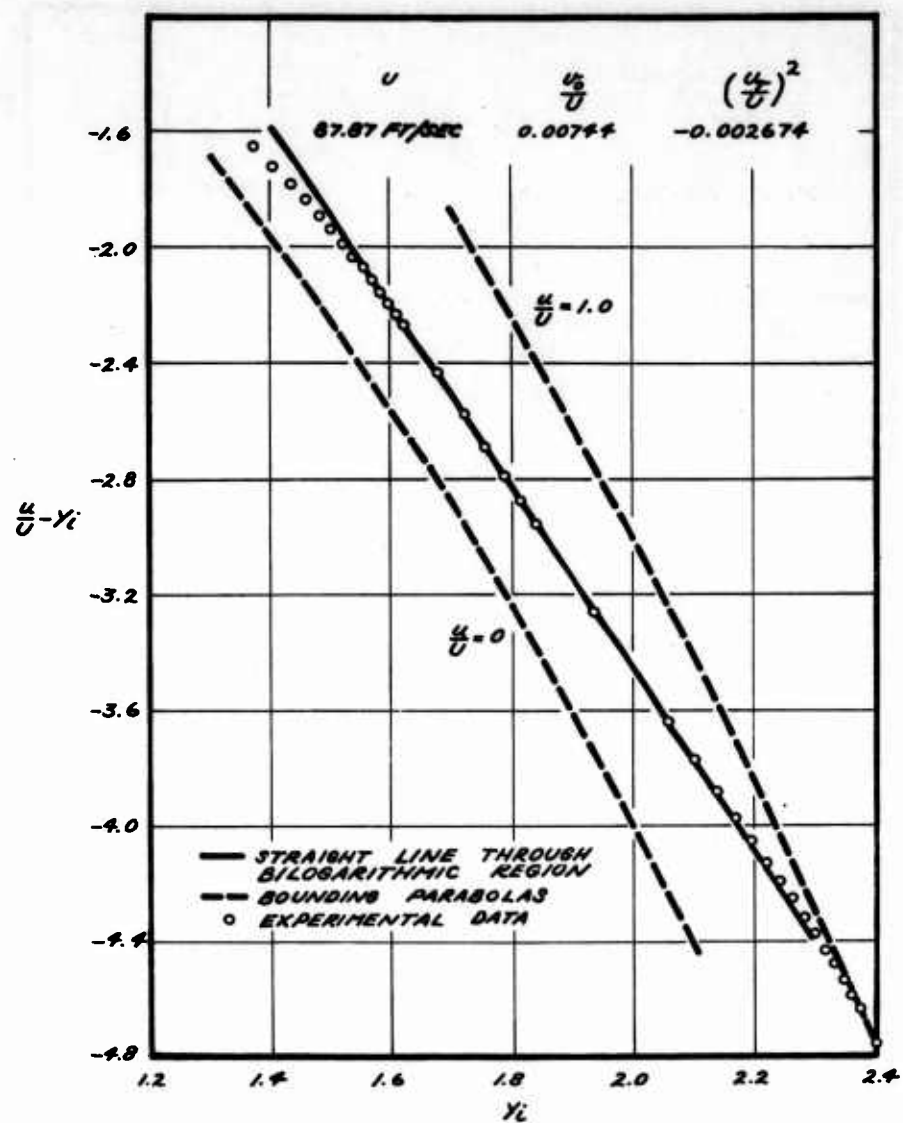


Figure 9. Method of Black and Sarnacki for Determination of Skin Friction with Injection.

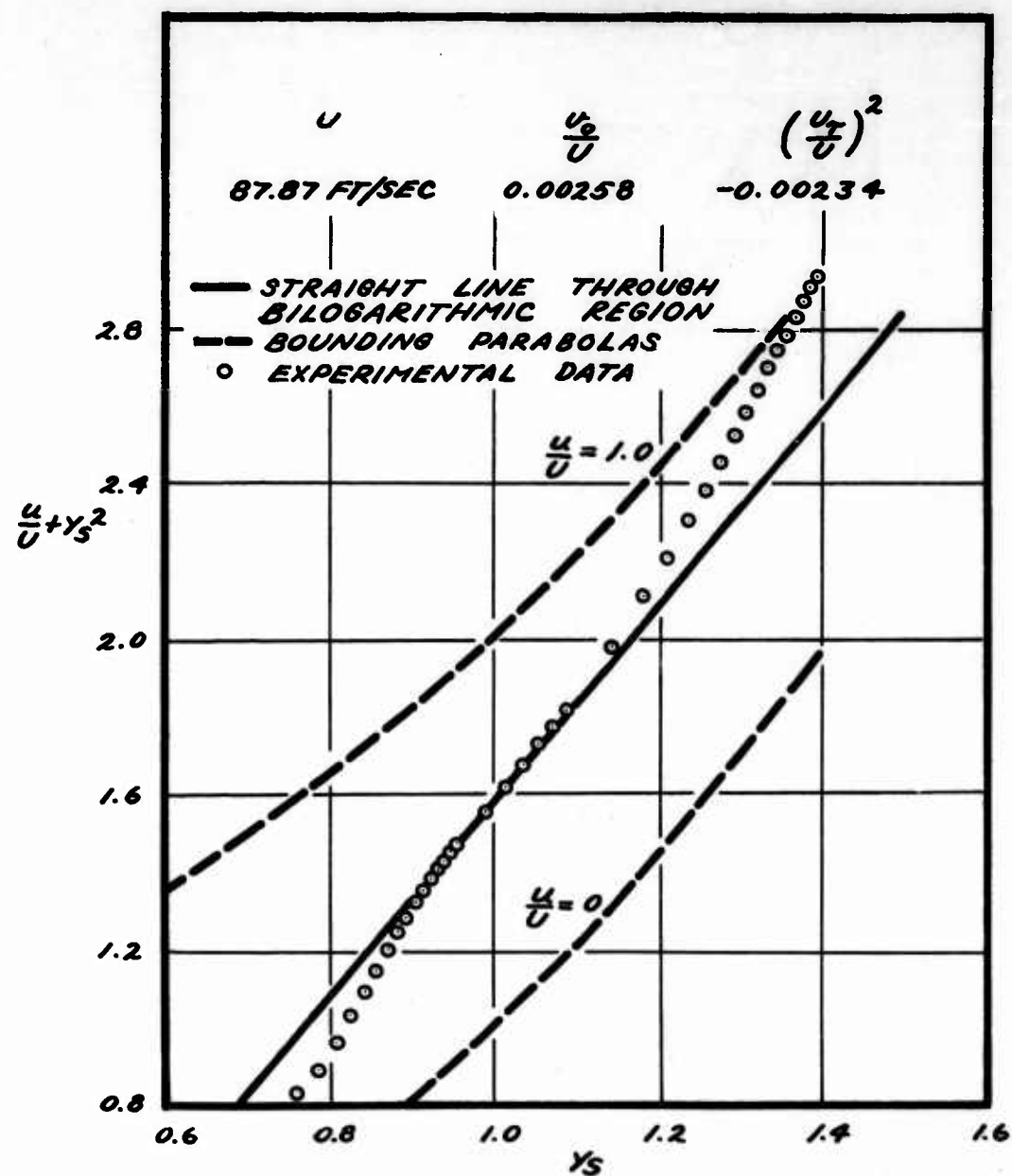


Figure 10. Method of Black and Sarnecki for Determination of Skin Friction with Suction.

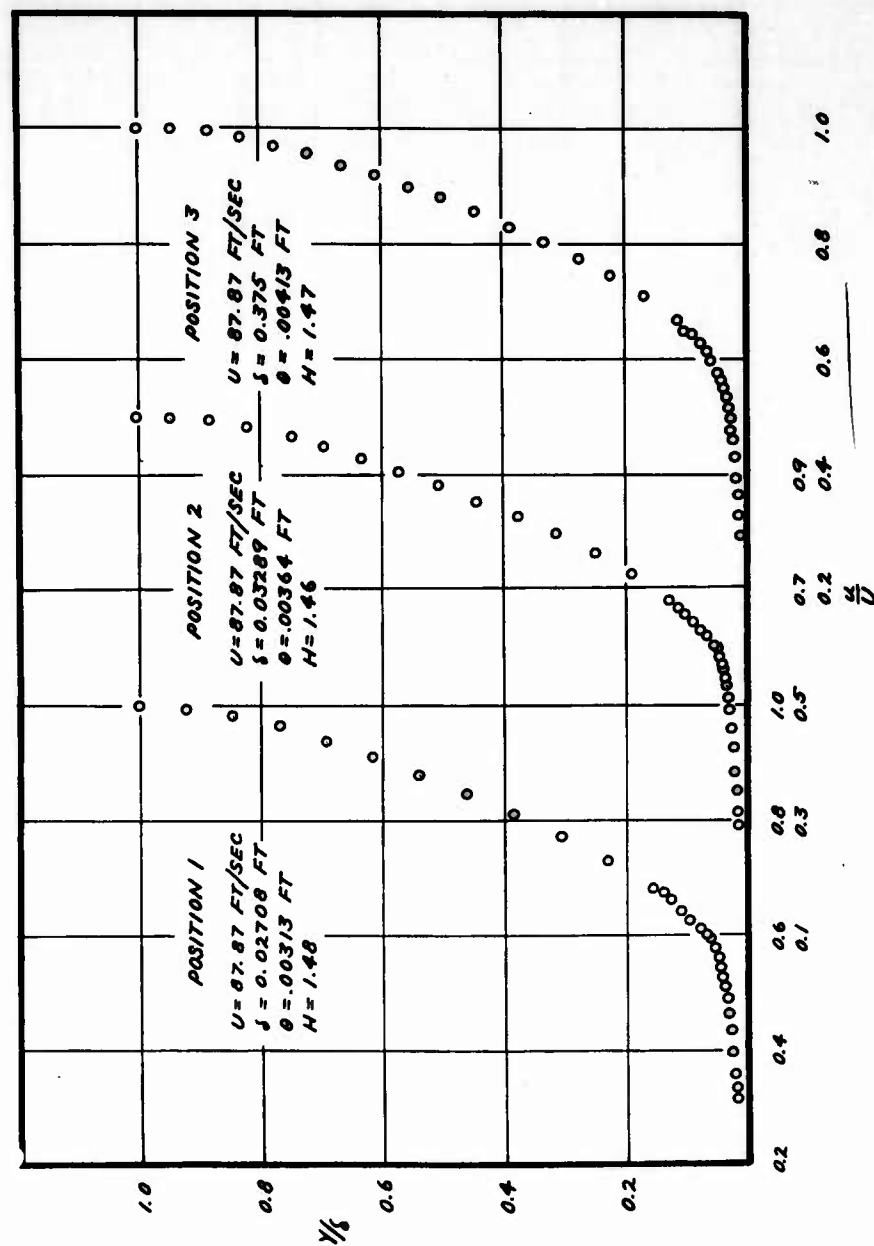


Figure 11a. Boundary Layer Profiles Measured on an Impervious Flat Plate.

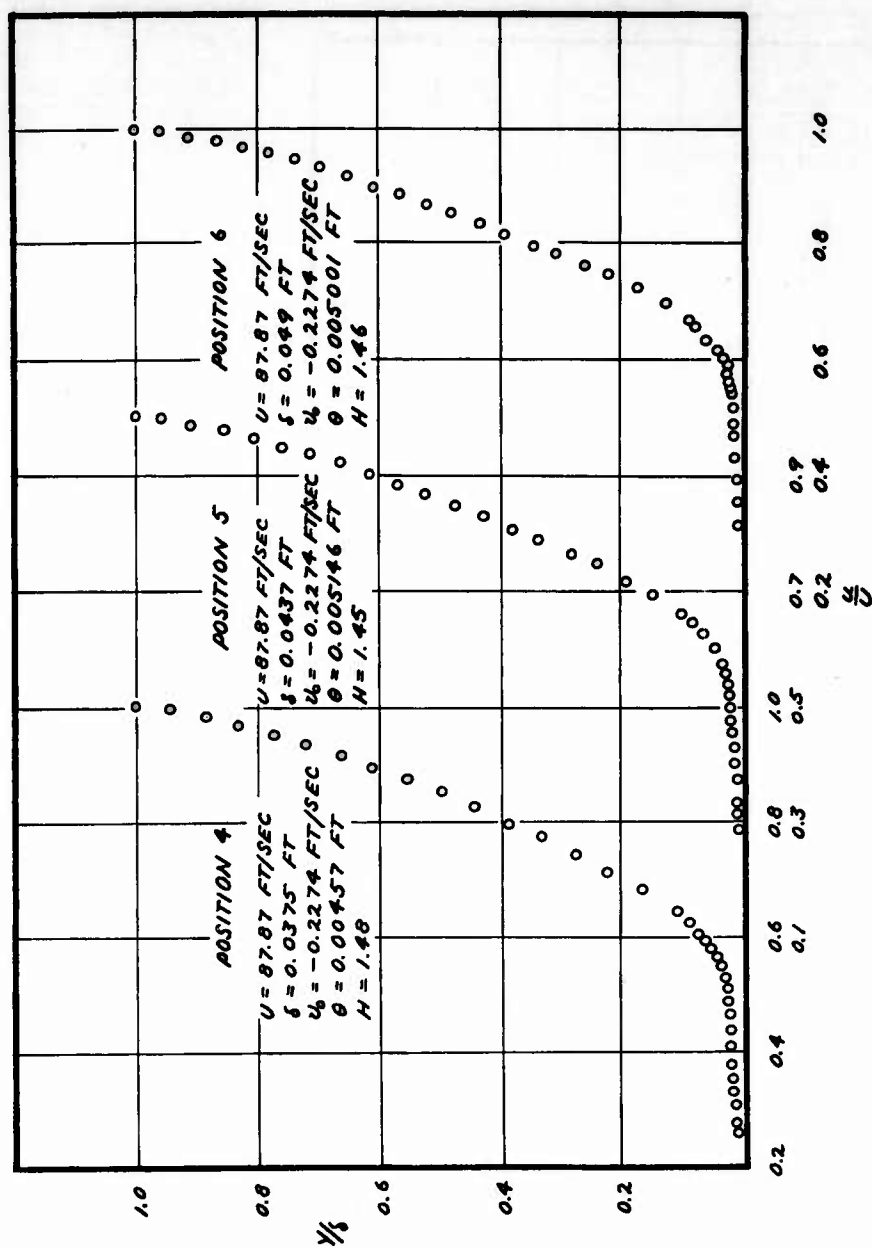


Figure 11b. Boundary Layer Profiles Measured on an Impervious Flat Plate.

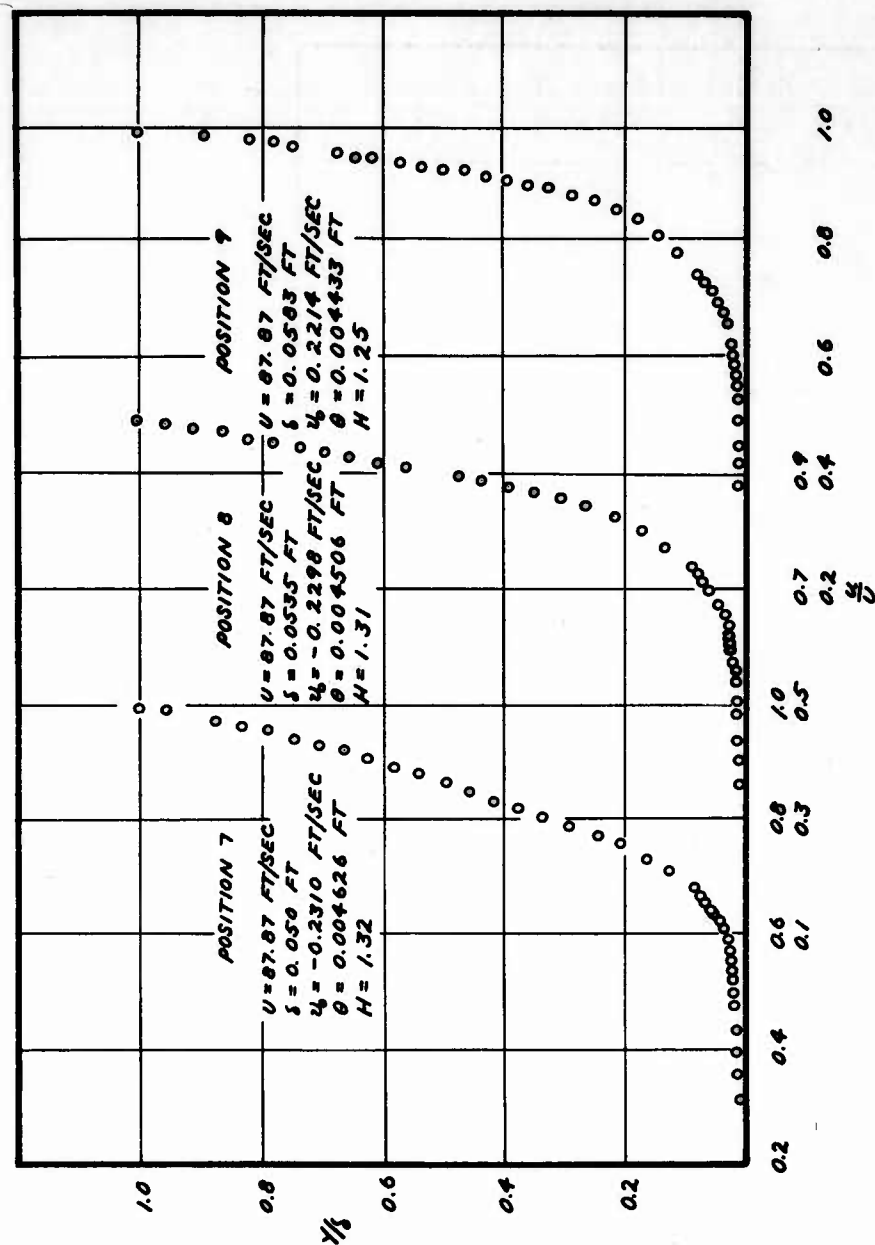


Figure 11c. Boundary Layer Profiles Measured on an Impervious Flat Plate.

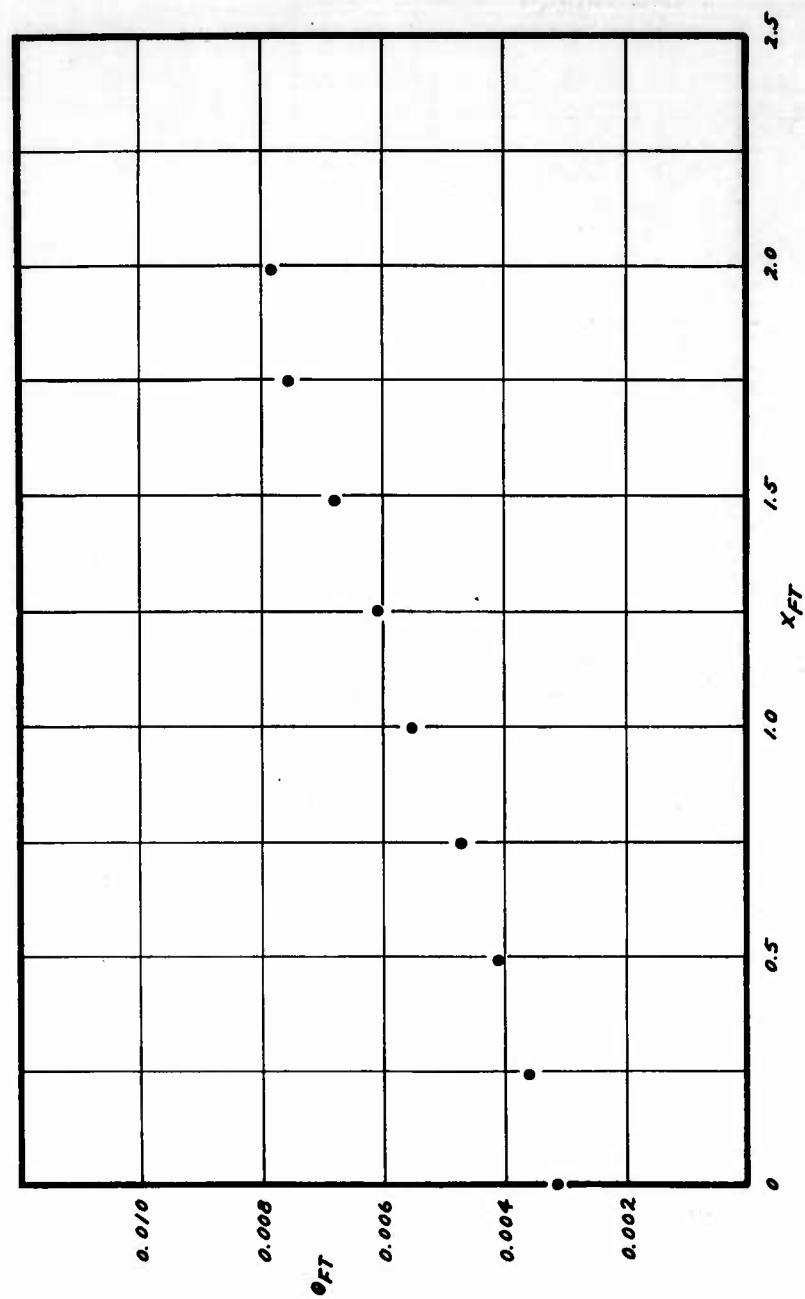


Figure 12. Development of Boundary Layer Momentum Thickness.

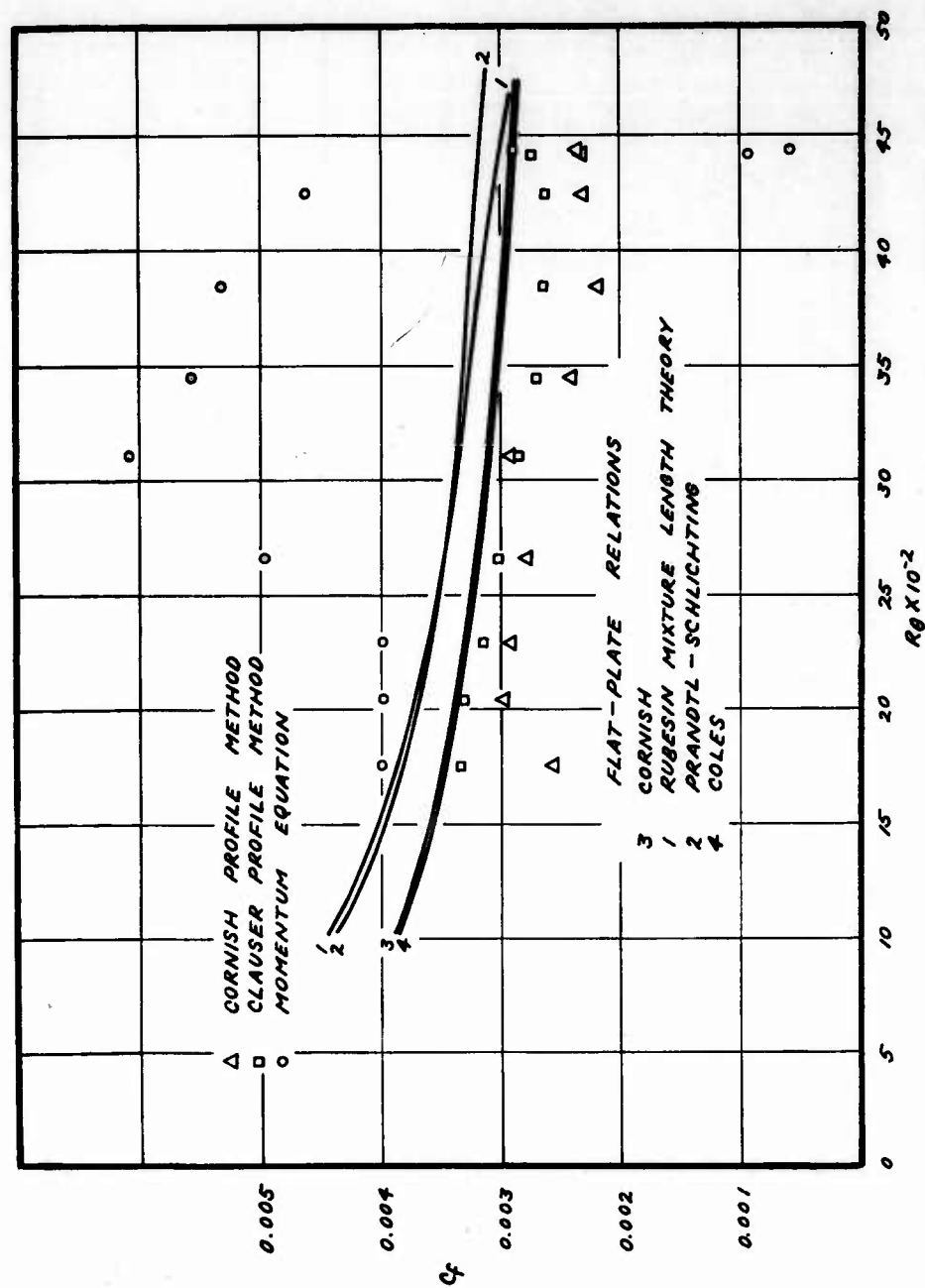


Figure 13. A Comparison of Turbulent Skin Friction as Determined by Various Methods.

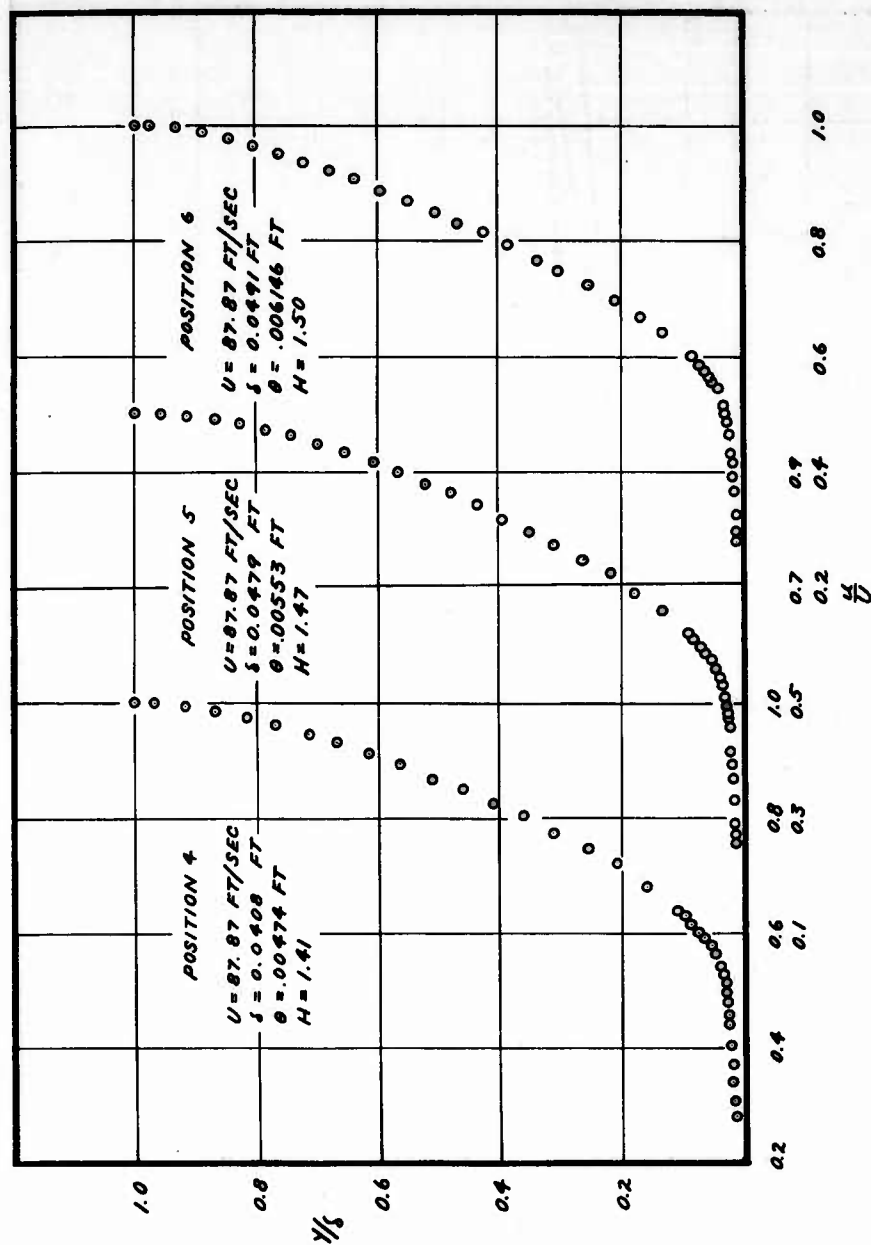


Figure 14a. Turbulent Boundary Layer Profiles with Section at Surface.

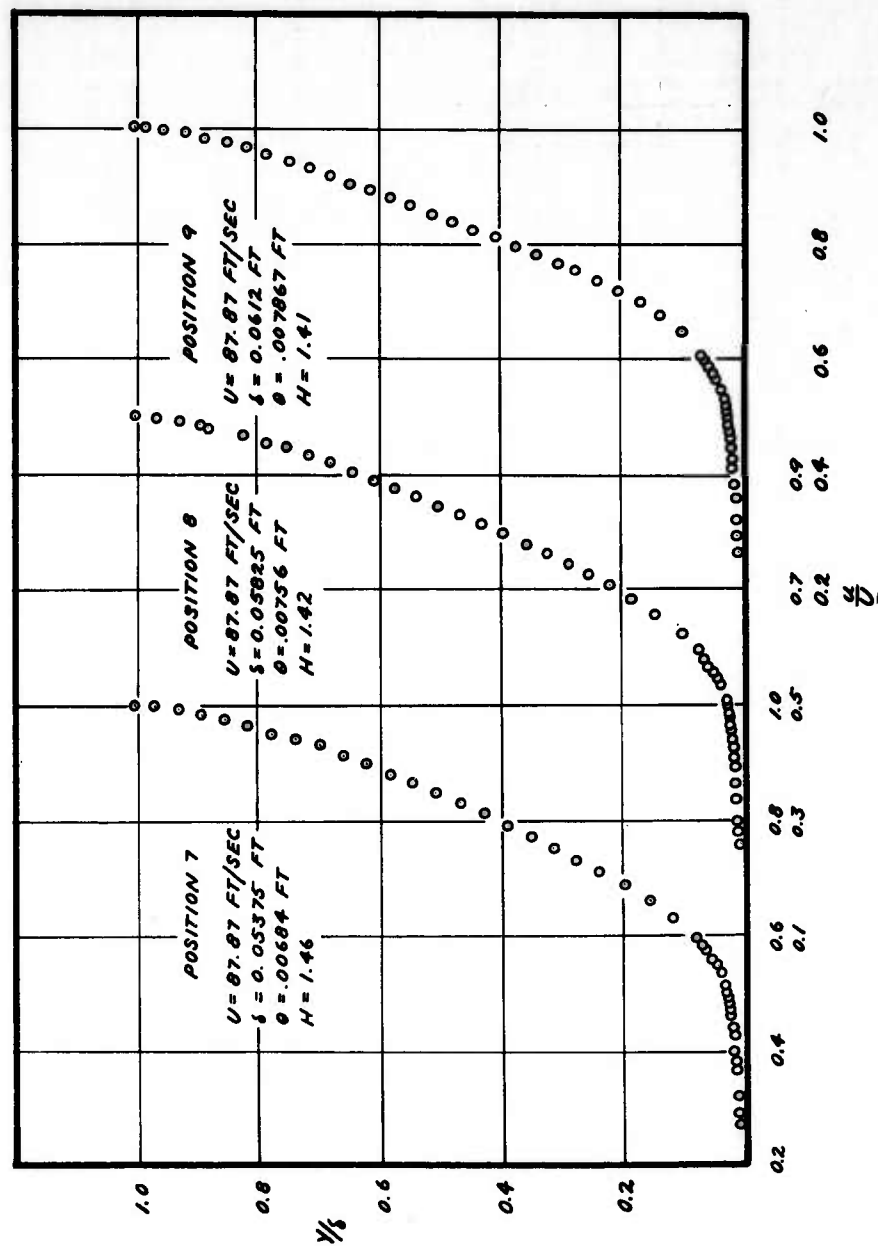


Figure 14b. Turbulent Boundary Layer Profiles with Suction at Surface.

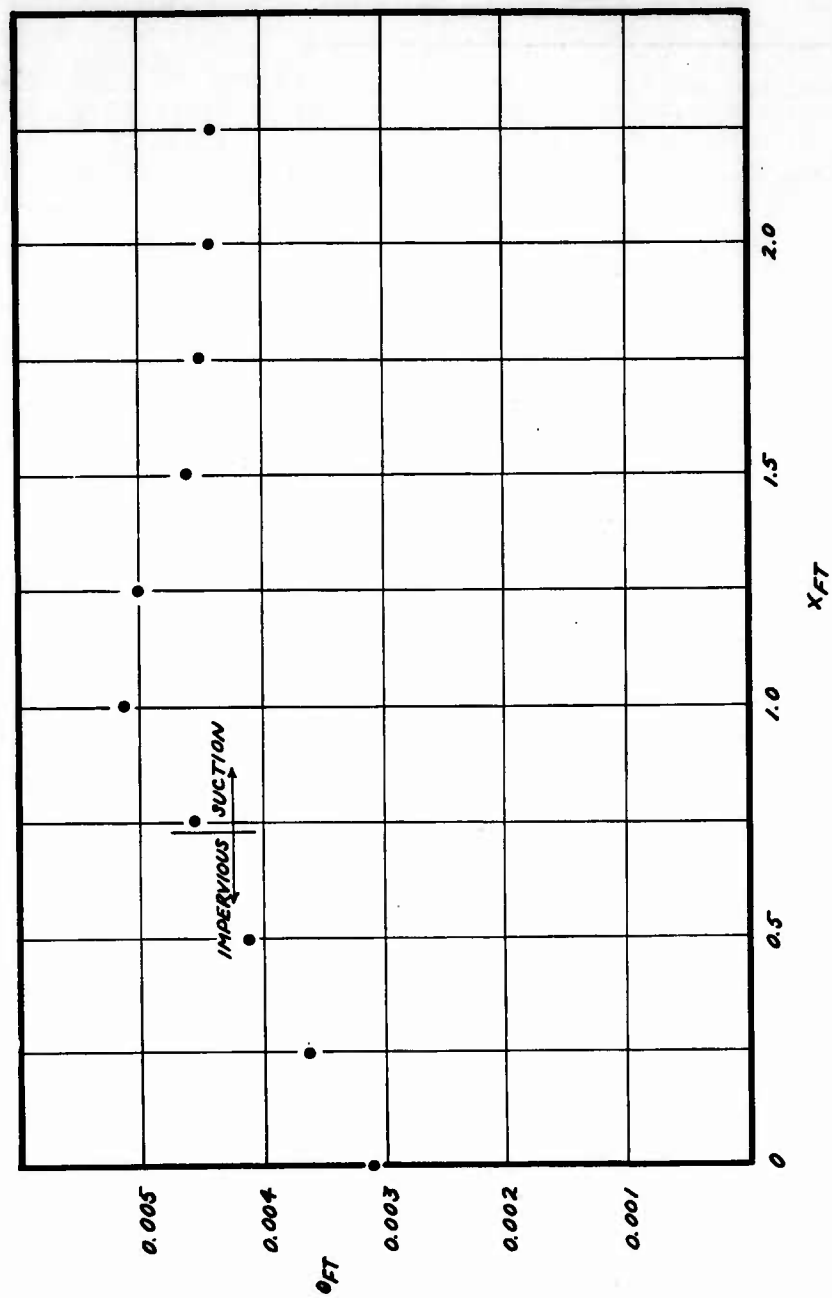


Figure 15. Development of Boundary Layer Momentum Thickness with Suction.

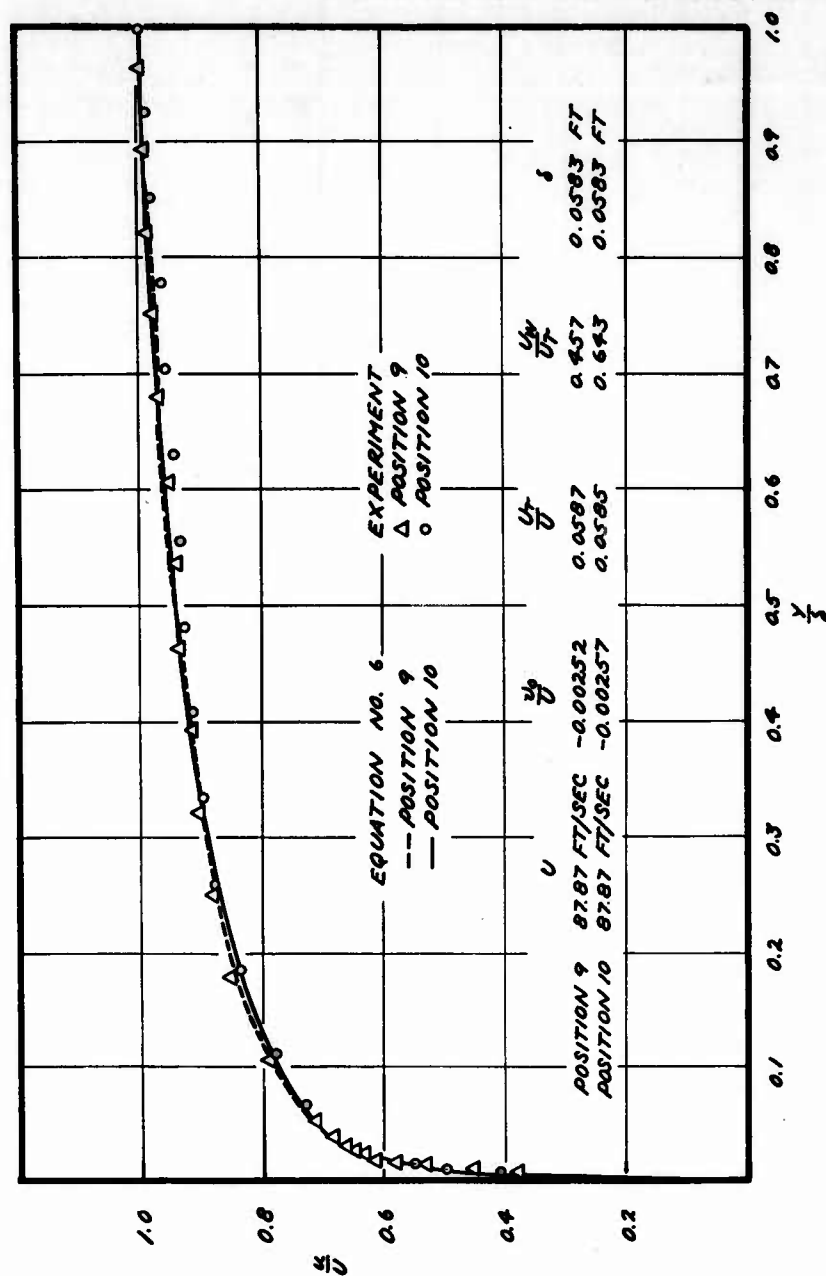


Figure 16. Examples of Asymptotic Turbulent Boundary Layer Profiles.

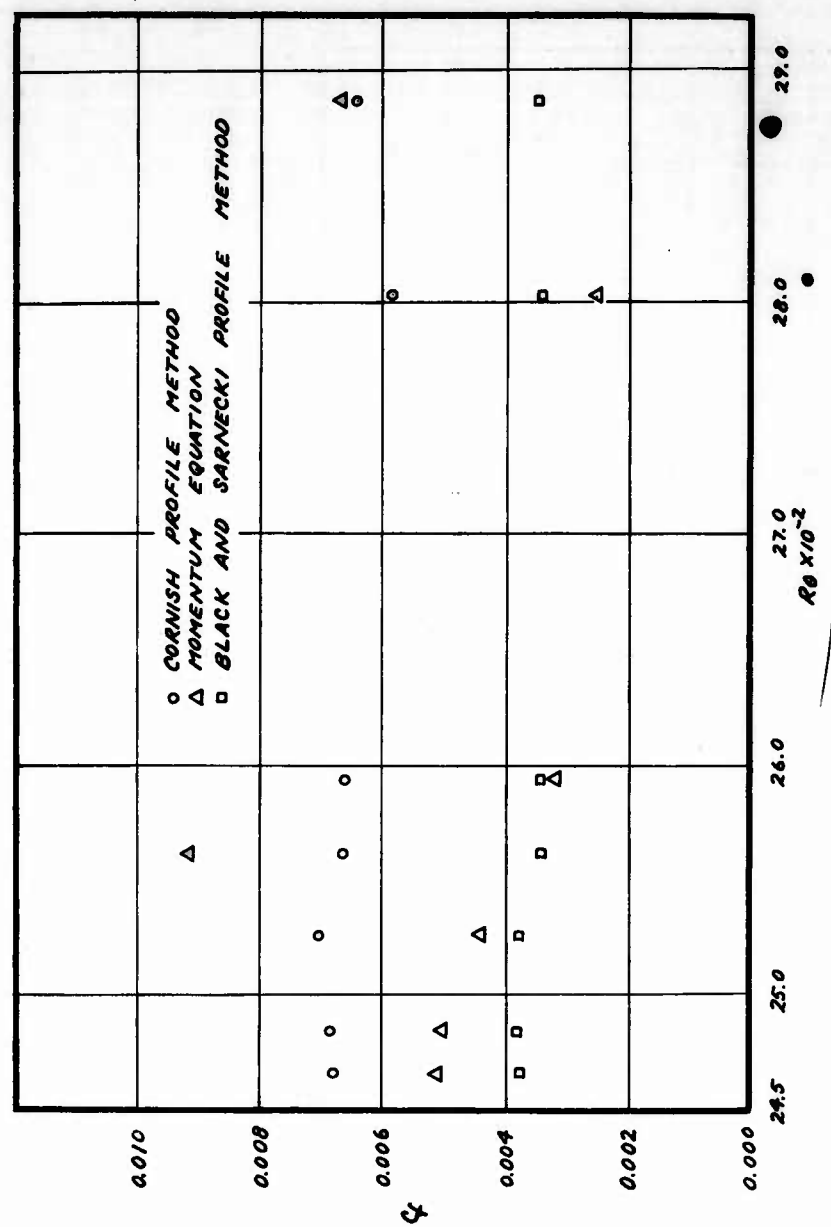


Figure 17. A Comparison of Turbulent Skin Friction as Determined by Various Methods.

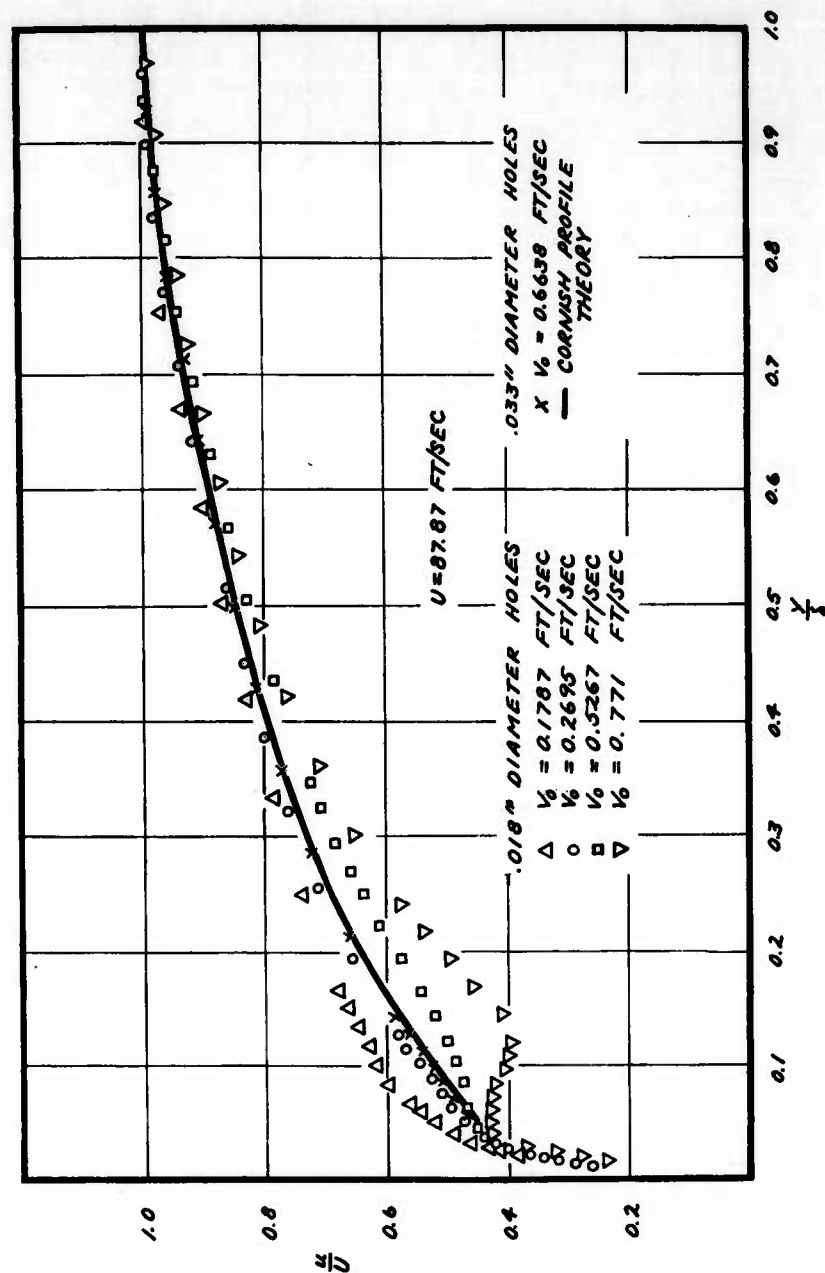


Figure 18. Effect of Discrete Injection on Boundary Layer Profile Shape.

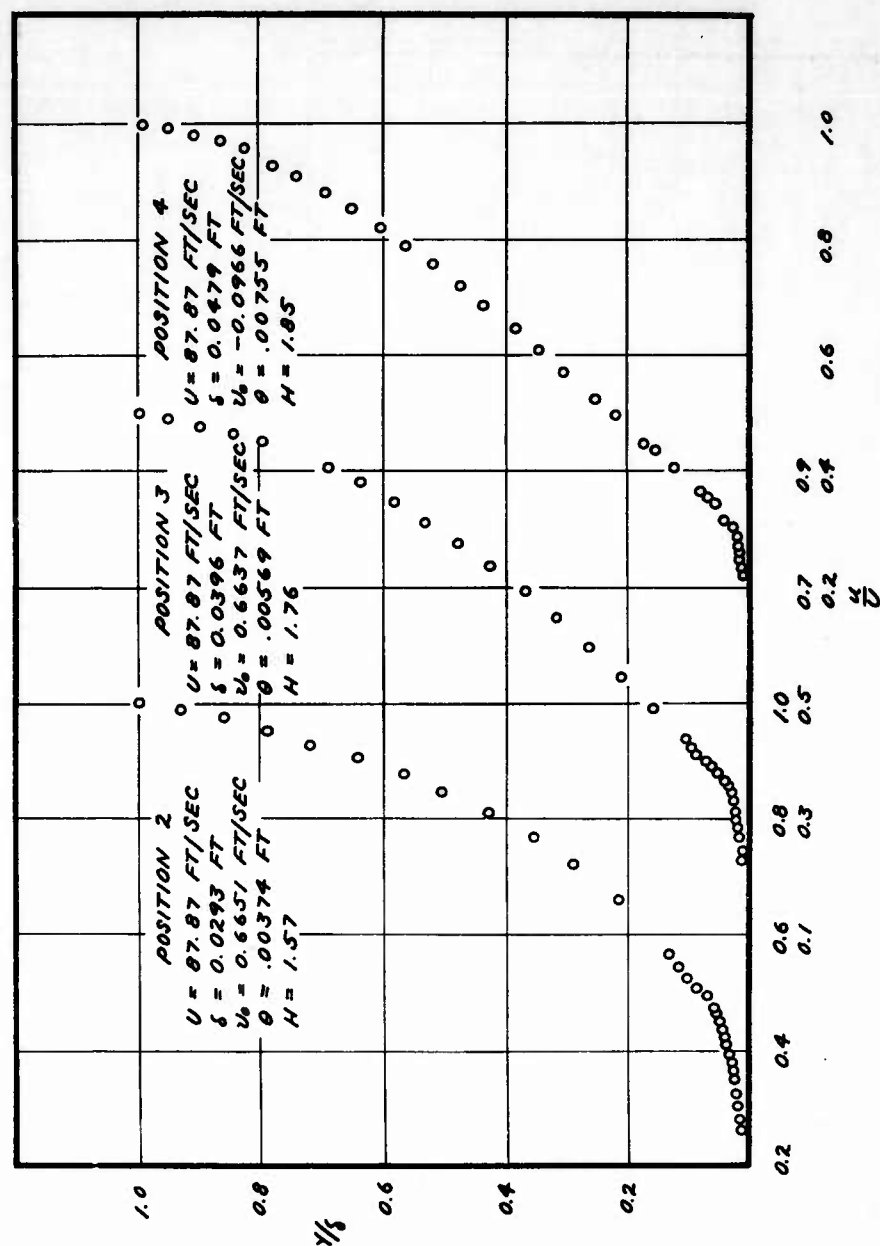


Figure 19a. Turbulent Boundary Layer Profiles with Injection and Suction at Surface.

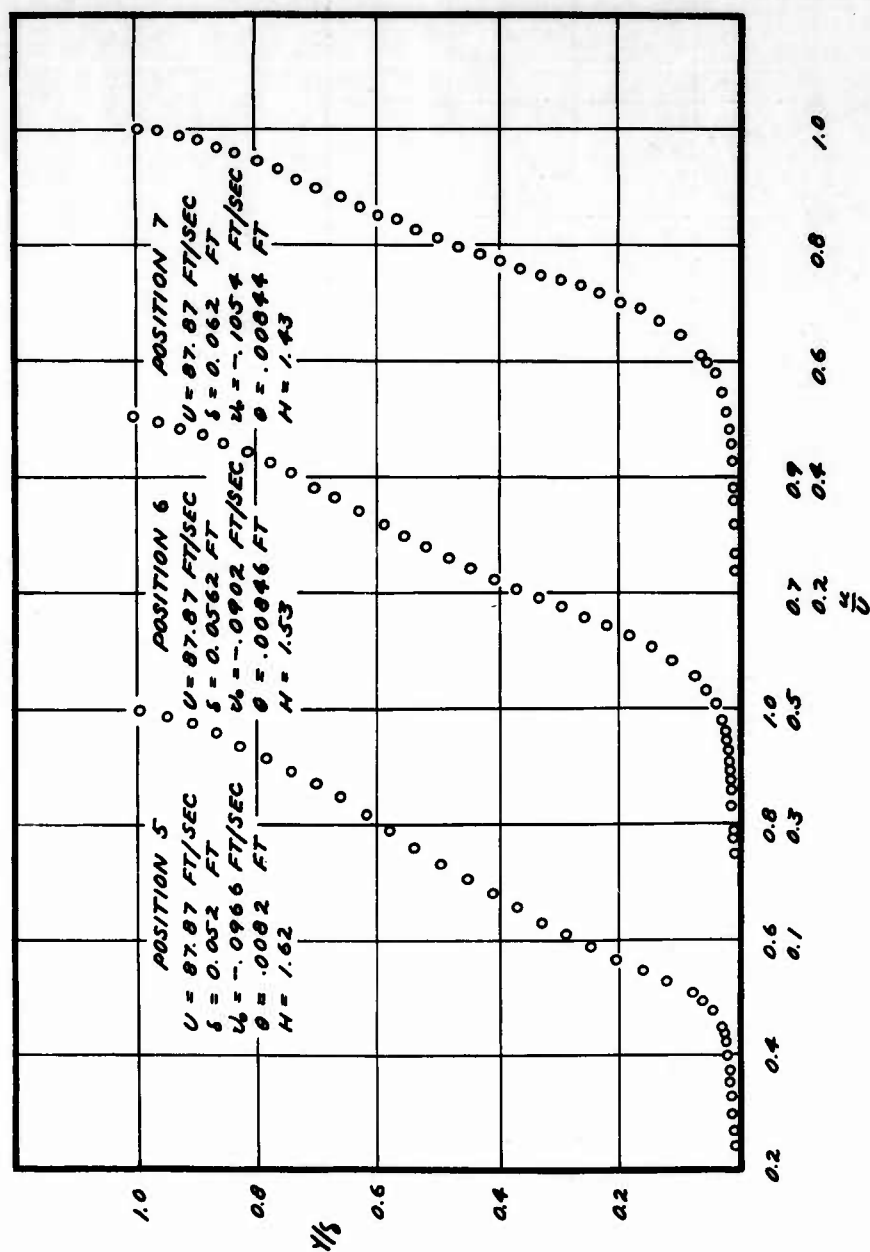


Figure 19b. Turbulent Boundary Layer Profiles with Injection and Suction at Surface.

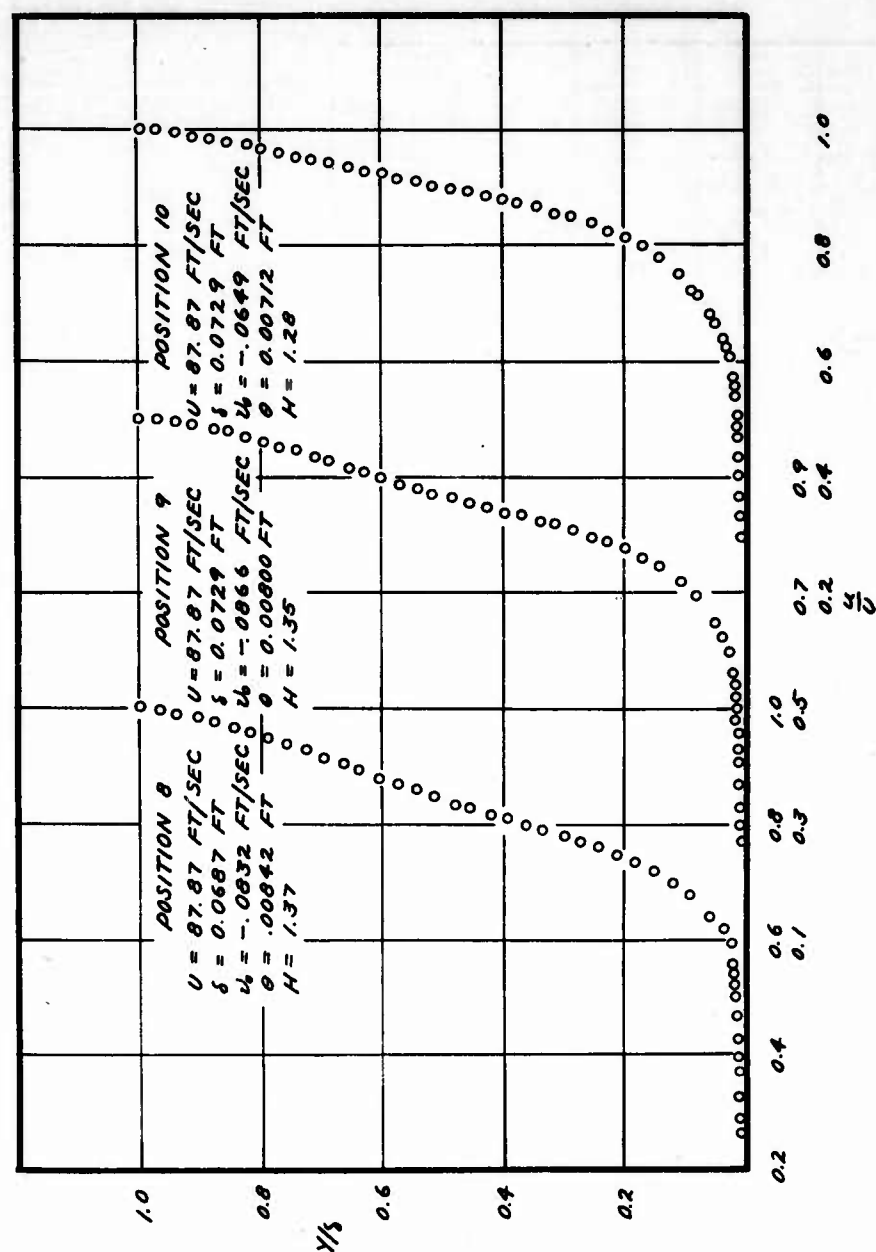


Figure 19c. Turbulent Boundary Layer Profiles with Injection and Suction at Surface.

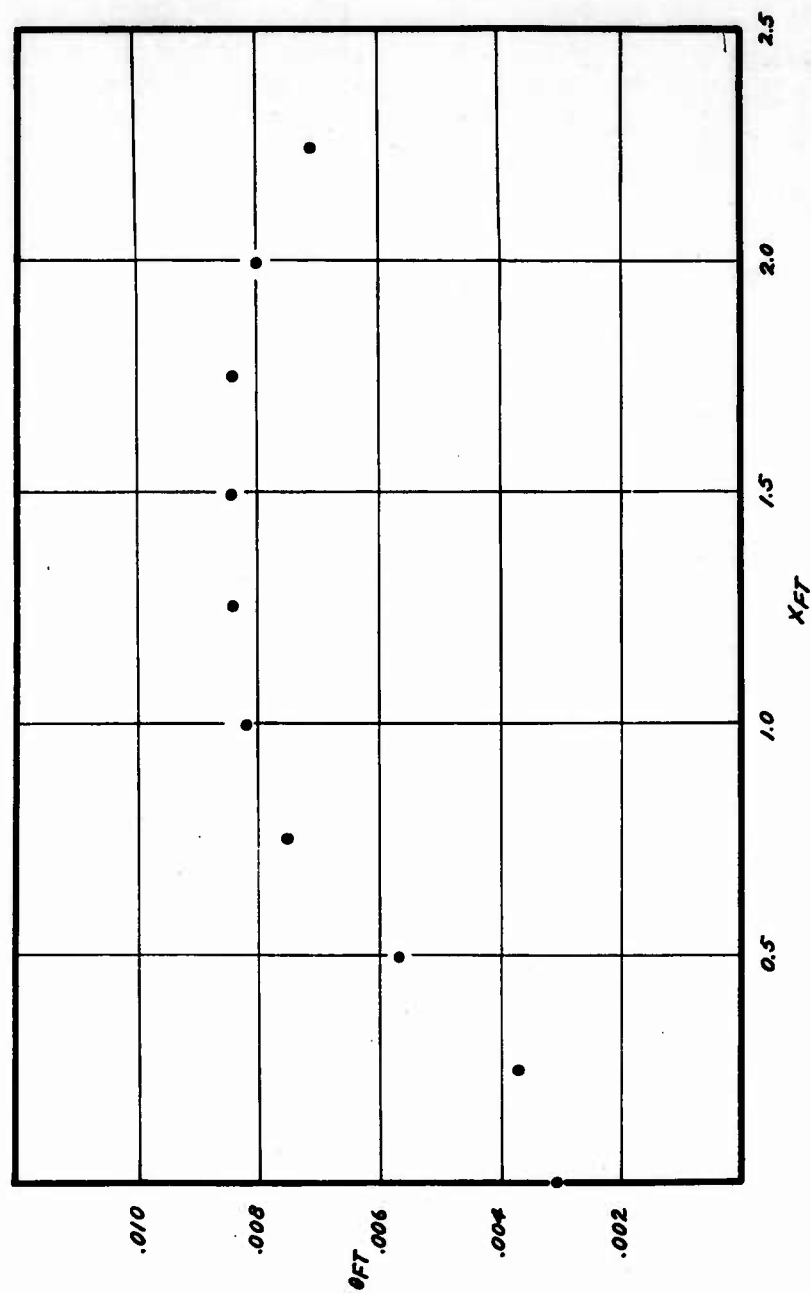


Figure 20. Development of Boundary Layer Momentum Thickness with Injection and Suction.

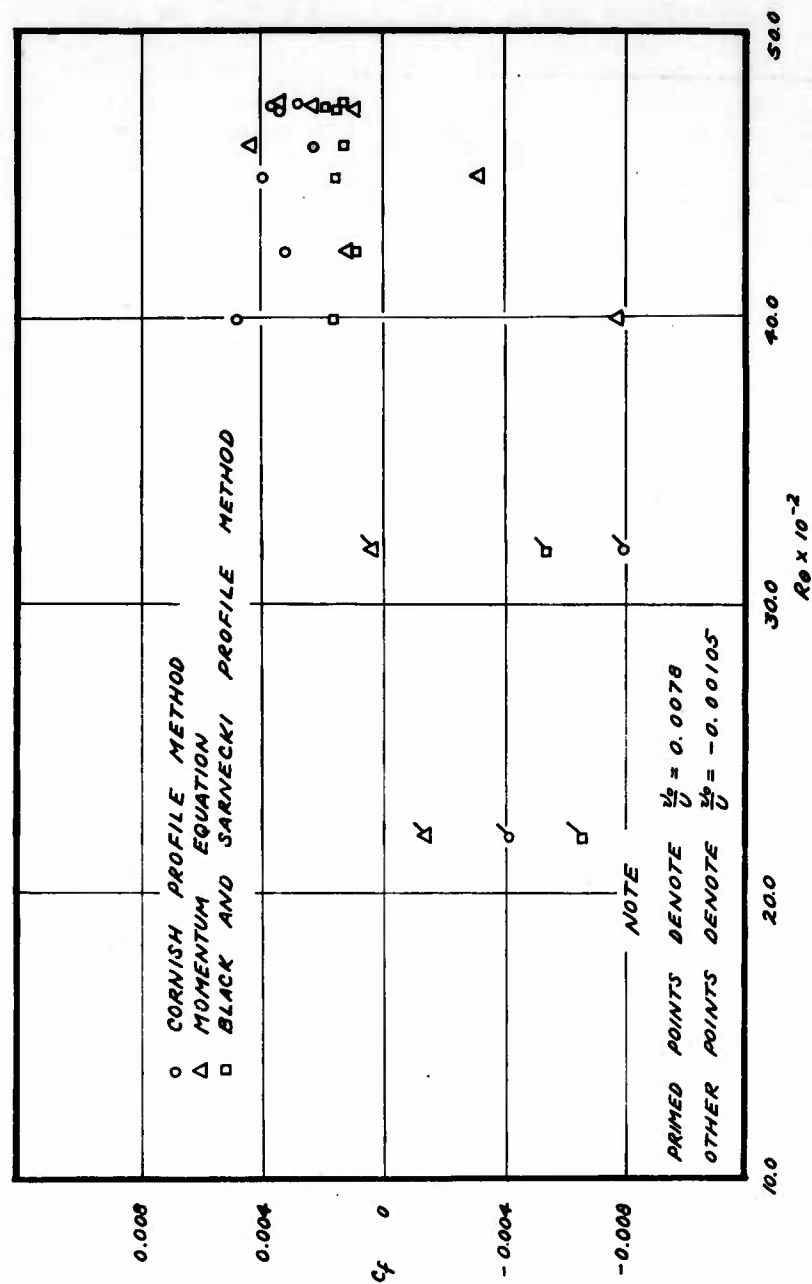


Figure 21. A Comparison of Turbulent Skin Friction as Determined by Various Methods.

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USATRECOM Task 1D121401A14203

Unclassified Report

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None of the methods could be shown to be more accurate than the others but the momentum balance method was the least consistent.

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